Hydro Power is not Forever

A Research on the Sustainable Management of Water-Dependent Electricity Generation with a Focus on Reservoir Sedimentation

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OVERVIEW

The modern Anthropocene would not exist without electricity. It is the ticking clockwork that guarantees and dictates the rhythm of modernity in all of its beneficial and challenging extents. Electricity generation is a complex process with various inter-dependencies. It is thus important to survey, maintain and continuously adapt all contributors to guarantee a stable electricity generation.

This is all the more valid as humanity became aware of the negative repercussions of its constant striving for growth and wealth that provoked various threats, ranging from the climate change over poverty to health issues. In this light, the Sustainable Development Goals were created that should help to assess and guide humanity to a more sustainable way of thriving. The Sustainable Development Goals address several targets, one of them being sustainable (electric) energy supply.

The electricity generation's dependencies are manifold and certainly dependent on the type of generation, but one constant prerequisite is (almost) inevitable for nearly every type of electric generation facility: water. There exists a vast energy-water context with various threads of dependency. It is safe to say that electricity generation without continuous water supply is not secure. And though water is also a special target within the Sustainable Development Goals, the analysis and evaluation of those inter-dependencies between energy and water are scant. Few are the tools that exist to survey, assess and remedy energy-water context challenges.

What is more, electricity as pillar of our Anthropocene is already a globally implemented infrastructure that demands constant management action. Yet, the research of the sustainable and secure energy-water context management on its various levels - ranging from macro-scale analysis and strategy development over meso measures of transference to the mindset behind the micro actions that maintain the electricity generation - is not too advanced, though the topic is of utmost importance.

This dissertation investigates on various levels to develop and survey methodologies that reveal and remedy the energy-water context challenge. It does so with five studies. Three of them investigate the special issue of reservoir sedimentation as a prime example of threatened energy-water infrastructure, whose management needs to be surveyed. Out of the five articles, one is already published, one is in press and three are under review. The research will be presented in five chapters.

Chapter 1 prepares the ground of the thesis as an introduction. The nature of energy-water dependency is demonstrated and the lack of energy-water sustainability research outlined. On various levels, central research questions for sustainable and secure energy-water management are developed for the thesis. As reservoir sedimentation as a special case and artificial neural networks as a research methodology are of key importance, their principles and backgrounds are illustrated.

Chapter 2 surveys the possibilities to evaluate, analyze and assess the multifaceted nature of water-dependent electricity generation. It lights on an essential gap of holistic energy-water security assessment and fills this gap with a broad methodological approach for holistic energy-water security assessment.

In Chapter 3 the transference of developed energy strategies to the level of application for an energy-water-(food)-context is investigated. A gap between public professionals and other stakeholder groups as major inhibitors is identified. Within the chapter, an approach to overcome this gap is developed and investigated in a case study in Ouarzazate, Morocco.

Subsequently, the degree of security and sustainability thinking of the mindset behind applied energy-water management action is subject to investigation in Chapter 4. This is executed using the example of reservoir sedimentation in Japanese reservoirs. The optimism bias, an influential and non-sustainability mindset in infrastructure management, is used as a proxy to do so. Artificial neural networks serve as a prime tool to derive evidence.

Management action is bound to have (expected or unexpected) effects. In the case of reservoir sedimentation in Japan, a mass data methodology based on artificial neural networks is developed in Chapter 5 to extract traces for such effect. It is based on a thorough data set of 1225 Japanese reservoirs with (among others) individual 18 year sedimentation and precipitation time series as well as continuous management action notations. The key element is a Gated Recurrent Unit (GRU) core of the neural networks that allows a memory function. The extensive research reveals evidence of concrete management action on a meso scale.

The conditions of the energy-water context are globally quite different. Chapter 6 is another case to survey the effect of management action, investigating again via artificial neural networks on reservoir sedimentation. This time, the study is settled in the state of Ceará in Brazil and the focus object is a certain, presumably sustainable, management directive of the state governance.

The results are discussed in Chapter 7, where a conclusion and outlook of the dissertation is given.

The dissertation reveals the Gordian web of multi-leveled governance and management of the complex energy-water context. It is emphasized that the presented findings are not the only way to respond to the established research questions, since the results are by no means of panacea character. Rather, the outcomes of the dissertation are very worthwhile tools that bear the flexibility of being applied to the highly variable challenges of the energy-water context. The dissertation is thus a valuable contribution to establish a secure and sustainable utilization of (water) resources and (electricity) infrastructure within the modern Anthropocene.

Dedicated to my family
-
I know you will not read this dissertation (completely)
but I love you either way
I am grateful and proud to share my life with you

Our mission is to remove any barrier which is impeding the widest
possible distribution of knowledge in human society!
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limits to knowledge distribution.
-
Alexandra Elbakyan, creator of Sci-Hub

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CHAPTER

1 INTRODUCTION

The world has entered the era of energy transition. The pace of conversion to renewable energy might be slow, but pace is not the crucial point to define, whether the world has entered energy transition or not. Rather it is the transition's acknowledgment around the globe. Countries with all types of government forms have shifted paradigms and recognized the need to fuel their societies with electrical energy that is based on so-called renewable sources (Hafner and Tagliapietra, 2020).

> At this point of the dissertation, it is stressed that the term *energy* will be utilized synonymously with *electrical energy* or *electricity*, if not specified otherwise. The various different means of energy utilization (e.g. gasoline for mobility) are recognized, but do not form part of the research presented.

In addition to efforts to mitigate the climate change via the reduction of greenhouse gas emissions, one of the principal drivers for actors is to become independent of energy carriers and their supply chain. This will elevate energy security. Sources of energy are hence sought that are seemingly immaterial, trans-boundary and apparently endless or renewable - and thus secure (Ahmadov and van der Borg, 2019; Hafner and Tagliapietra, 2020). A necessary resource that underlies most, if not all electricity generation types is, however, frequently overseen: water (Ziolkowska and Peterson, 2016).

Water is a perpetual precondition for energy generation, be it renewable or fossil, as will be explained in Chapter 1.1. It is thus a key resource in this transition phase where both renewable and fossil energy generation play a major role in the upkeep of the contemporary rhythm of the Anthropocene, that is determined by electrical energy (Tully, 2006; Ahmadov and van der Borg, 2019; Hafner and Tagliapietra, 2020). It exists as an energy-water dependency. The evaluation of the energy-water dependency, the transference and implementation of strategies to manage the energy-water dependency, the mindset behind said management and the very effect of management action on the water-energy dependency, are scant and insufficiently examined topics.

> Energy is dependent on water. However, the relations between energy generation and water supply go way beyond a mere dependency. Especially Chapter 2 will show this. Hence, it is not sufficient to name the relation between energy and water merely energy-water dependency. A vast mix of different disciplines and topics (e.g. governance, competition or feedback effects (see Chapter 2.5)) do have their share, when energy generation is conditioned by water. Thus, the slightly vague but all the more flexible term *energy-water context* will be used throughout this dissertation, to refer to this interdisciplinary and multi-faceted relationship.

The following introduction will illuminate major backgrounds of the energy-water context and this dissertation. It will explain why electricity generation is (almost) inevitably dependent on water in Chapter 1.1 and demonstrate the lack of energy-water integration on various management and governance macro to micro levels in Chapter 1.2. Based on this, the dissertation's research structure and research questions will be elaborated on and structured in Chapter 1.3. Subsequently, crucial background information about the specific energy-water problem of reservoir sedimentation and the Artificial Neural Network research methodology used will be fleshed out in Chapter 1.4 and Chapter 5.2.2, respectively, as the two elements were fundamental for the creation of responses for two of the four research questions.

1.1 What is energy and why is electric energy generation (almost completely) dependent on water?

Coal burns, sunbeams are hot, wind blows fast and water runs downwards. Energy is perceivable or even palpable to the human mind. The main components of energy perception for the human sensory system are: heat and force.

The energy stored in water is evident by its force, for example when falling down a waterfall. The water's utilization via hydro power plants and the conversion of its force to electricity that can be accessed by human society appear to be a logical and, in its principles, an easily understandable process of energy generation. The dependency of this hydro power type of energy generation on water is likewise easily understandable.

The utilization of the energy stored in coal or sunbeams via thermal power plants and its conversion to electricity seems equally logical. Their dependency on water, however, is not evident. Where does the water come into play? To find access to the dependency of electrical energy and water, a definition of energy is necessary.

The multifaceted character of energy is represented by the definition of its standardized SI (International System of Units abbreviated from the French Système International (d'unités) unit, the Joule (Benenson et al., 2002a,b,c). The presentation of the units instead of the physical variable gives a more direct understanding of (one unit of) energy:

$$J = \frac{kg * m^2}{s^2} = e * V \tag{1.1}$$

J = Joule
kg = kilogram
m = meter
s = second
e = elementary Charge
V = Volt

The equation shows three important characteristics of energy:

1. The expression in the middle illustrates kinetic energy - this also includes heat, as will be demonstrated later.

2. The expression on the right illustrates electrical energy.

3. Energy is 100% convertible, it cannot simply disappear.

According to Equation (1.1), one unit of energy, the Joule, is represented by SI (standard) units.

1.1.1 Kinetic energy and water

The expression in the middle illustrates kinetic energy: $\frac{kg*m^2}{s^2}$. This can be translated into a conceivable image: A body of $1kg$ (e.g. a small Hokkaido pumpkin) is accelerated (increase of velocity m/s over a period of time, i.e. $\frac{m}{s} * \frac{1}{s} = \frac{m}{s\check{s}}$) by $1\frac{m}{s\check{s}}$ over a distance of $1m$. This represents one Joule, one unit of energy (Benenson et al., 2002c).

In the case of hydro power, the acceleration of a (liquid) body is vividly put into action. Either the natural flow of rivers is used to spin (to accelerate) a turbine (which itself is connected to a generator that finally induces electric energy in conductors). This is called a run-of-river power plant, or water is retained by a dam to form a reservoir. This induces a head of water and therefore a drop height, that again is used to spin a turbine (Dixon and Hall, 2014).

1.1.2 Electric energy

A little more difficult is the visualization of energy in the form of electricity, that is represented by Equation (1.1). The expression $e * V$ is called the electronvolt. It is defined by the elementary charge e, which is a natural constant. Simplified, the elementary charge is exactly the charge that one electron, the elementary particle of an atom, carries. A Joule is thus the energy that an electron experiences when it is "electrically accelerated", i.e. put under the tension of $1V$, which makes it travel in conductors like a copper cable (Benenson et al., 2002a).

1.1.3 Heat and entropy

Similarly abstract is the concept of heat. Heat is also defined by $\frac{kg*m^2}{s^2}$. It becomes palpable when atoms, the smallest chemical units, that consist of elementary particles like electrons, neutrons and protons, are imagined as (randomly) moving or vibrating objects within solids, liquids and gases. The kinetic energy of those particles is perceived as heat by the human mind.

To reveal the nature of heat, it is helpful to imagine the point at which no atomic movement takes place. A body or material that has (almost) no inner atomic motion is thus (theoretically, as the absolute zero cannot practically be reached) absolutely cold, which is defined as temperature of $-273,15$řC or $0K$, that is zero Kelvin. Every other object with more atomic motion has a higher temperature.

Now a body A with zero atomic motion and a body B with atomic motion (and thus with higher temperature) are hypothetically in touch with each other. Body B causes the atoms in Body A to vibrate whilst its own atoms decelerate. Energy is transferred from body B to body A. This energy transference is perceived by the human mind (and is defined by thermodynamics) as *heat*. Heat is the energy transference of the atomic motion (Benenson et al., 2002b). It is hence the transference of temperature, i.e. kinetic molecular energy, of a warmer to a colder material or body.

It is important to note that heat transference only happens uni-directionally; warm to cold. This is rooted in the concept of so-called entropy.

The significance of entropy can be derived from its statistical definition that was established by Boltzmann (1868).

$$S = -K_b * \sum_i p_i * ln(p_i) | p_i = \frac{1}{N_i} \tag{1.2}$$

S = entropy
K_b **= Boltzmann constant**
p_i **= probability of the** i_{th} **different state**

N_i = **Number of different, equally likely states**

It demonstrates that the entropic likelihood for an ordered structure is far less than a non-ordered structure. When the number of states rises, the likelihood for each of them diminishes, which causes the entropy to rise as per definition of equation 1.2.

According to the logarithmic element of the equation 1.2, the smaller the number of states when the same N is changed, the more entropy increases. I.e. a rise from $N = 2$ to $N = 3$ will cause a higher rise in entropy S than a rise from $N = 3000$ to $N = 3001$.

Smaller N exist with lower temperature (as there is a lot less movement) and thus entropy rises more with lower temperature bodies heating up. This means that heat is bound to flow from warm to cold and not cold to warm, as the entropy rise in the warmer body will be lower than the one caused by the entropy rise in the colder body.

Especially at the phase transitions (melting, boiling), the number of states spikes upwards as e.g. atomic grid structures end to restrict atomic movements. This is demonstrated by Figure 1.1, where the entropy conditions are illustrated with a simplified example.

In the example of Figure 1.1, a solid has supposedly four firmly bound atoms and each one of them could liberally take up each of the four positions of the atomic grid (which is merely illustrative and not real). The body could have 24 different states. The liquefaction of said solid will cause the number of states to rise as the substance is now free from the grid restrictions. Subsequently, the entropy will rise tremendously, too, according to Equation (1.2). On the other hand, the external heat source will not take up heat as the theoretic rise in its molecular states will occur on an already level state. Its entropy rise will be a lot lower than the one achieved for the initially solid according to Equation (1.2). Thus, the heat source will induce heat and entropy into the initially solid body as this will lead to the highest overall increase of entropy.

The situation is comparable to a block of ice, which possesses a crystalline structure of limited statistical variance on molecular level. It has far less molecular states in which it can exist, than water (where the molecules of the liquid roam around more or less freely and chaotic). If one imagines a quantity of ice in an enclosed, isolated box with no in- and output, the ice will remain ice. When sufficient energy in the form of a heated body enters the box, the ice will melt in the vast majority of cases which will let the overall system experience a rise in entropy.

Equation (1.3), which was established by Clausius (1865) reveals a further characteristic of entropy: Its fixation on heat.

$$dS = \frac{dQ}{T} \tag{1.3}$$

dS = rise in entropy
dQ = transferred heat
T = Temperature

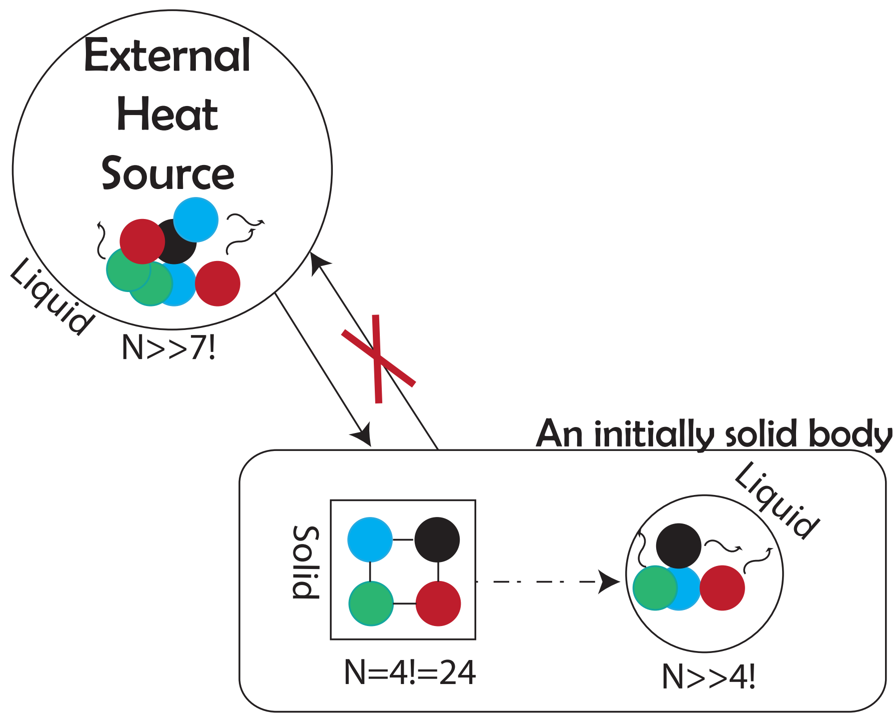

Figure 1.1: Simplified illustration of the heat direction that is determined by entropy via a phase transition example with N being the number of different, equally likely states

The quantity of entropy is represented by the division of heat and temperature. This implicates three conclusions:

1. There is no negative entropy. Entropy in a closed system thus cannot become less.

2. Entropy is bound to and transmitted by heat.

3. The higher the temperature T, the lesser the rise in entropy dS. One has thus to deal with less entropy if heat is transmitted between bodies of higher temperatures.

This has consequences for electricity generation.

1.1.4 Thermal electricity generation and water

In a thermal power plant, energy is transmitted by heat and converted to electricity according to Equation (1.1). Heat sources are manifold: Burnt coal/oil/biomass, concentrated solar beams or nuclear processes of disintegration are some examples. In either way, the power plant's heating source aims for very high temperatures to have less entropy (Sarkar, 2015a) which is concordant with Equation (1.3).

This has a reason and it is bound to the conclusions drawn from Equation (1.3): Electric energy has almost no relation to entropy, as the moving electrons that form electricity (see Chapter 1.1.2) roughly cause any heat (Dincer and Cengel, 2001). Entropy, however, must stay with heat and it cannot exist without it. But it cannot simply disappear. This implicates that not all heat can be converted to electricity. There must remain residual heat, i.e. a remaining energy transference between bodies of different temperatures that carries the entropy.

However, this remaining energy transference may happen at considerably lower temperatures according to Equation (1.3) than the initial heat source of the power plant. In power plants, this remaining energy transference is realized with a coolant, that takes up the remnant of heat and leaves the power plant (Sarkar, 2015b). The principle is displayed in Figure 1.2.

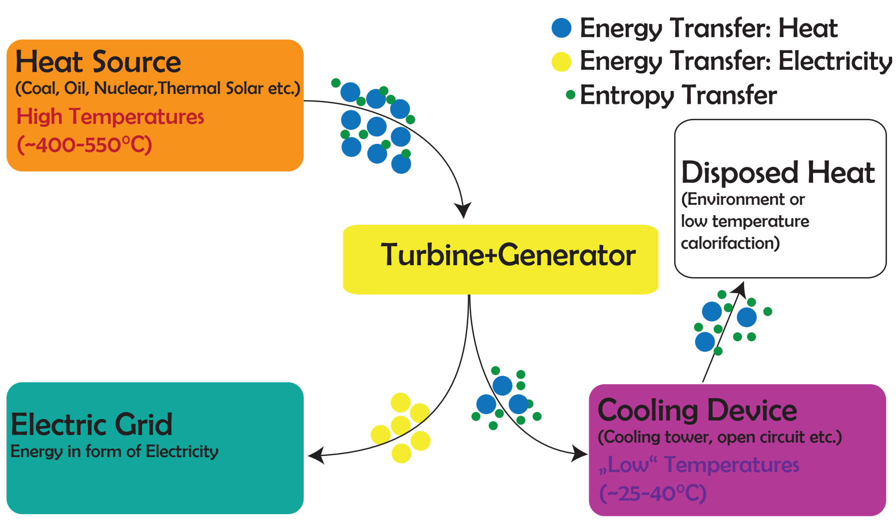

Figure 1.2: Simplified principle of energy and entropy transfer in thermal power plant

A material is thus needed as a remnant heat/entropy-receiver. The receiving process must be constant and the coolant must be moved away from the power plant site to give room for subsequent heat. It's a conveying process and thus a conveyor material is needed (Sarkar, 2015b).

For economic and practical reasons, the conveyor material ought to be: movable, cheap, abundant and disposable without impact into the ambiance (i.e. nature). Indeed, on earth, two materials exist that fulfill the criteria: Air (the mixture of various atmospheric gases) and water. Air is globally abundant, while water can be regionally abundant or scarce. Water, however, has a far higher specific heat capacity ($4.184\frac{kJ}{kg/K}$ at 20řC) than air ($1.005\frac{kJ}{kg/K}$ at 20řC) and can thus receive more heat per mass (and in a conveying process per hour) (Haynes, 2012). Water is thus way more efficient to transport entropy out of a thermal power plant than air. Where available (in abundance), water is generally used as a coolant conveyor.

Water is thus an essential and (almost) not negligible prerequisite of thermal electricity generation. The natural laws (almost) inevitably bind electric energy to water via entropy and kinetic energy. It is possible to generate electricity (almost) without water, as will be shown in Chapter 2.5. It is also possible to generate energy thermally (almost) without water. However, thermally it is unfavorable to not use water as a coolant.

1.1.5 The contemporary situation of water-dependent electricity generation

Data from the International Energy Agency (IEA) indicates that there are only two major types of contributors to global electricity generation that are not (constantly) dependent on water as a coolant or as a kinetic energy source: wind power and photovoltaics. As Figure 1.3 demonstrates, their former share in 1990 was extremely low (0.03%), but even their contemporary share in global electricity generation is limited: In 2018 it was estimated to comprise a mere 6.84%. Or, expressed differently: 93% of the global electricity generation depends on (fresh) water (excluding the shares of salt water and air cooling; more on this in Chapter 2.5) (International Energy Agency, 2021a).

The absolute rise between 1990 and 2018 in thermal ($10,875,610$ GWh) or hydro power ($2,133,437$ GWh) surpasses the absolute increase in wind and photovoltaics ($1,823,820$ GWh) by far (International Energy Agency, 2021a). This means that even though the share of water independent electricity generation was increased, more energy than ever in human history is dependent on constant water availability.

Water usage and hence water dependency for electric energy generation rose significantly in the last three decades. Subsequently, water dependency for electrical energy is an inevitable topic that needs to be addressed by governance and management.

The lifestyle of the Anthropocene is not imaginable without electricity. As shown above, electricity is (almost) not imaginable without water supply. To sustain modern human development, the safeguard of both electric energy and water supply are mandatory. A modern human society is not sustainable if it avoids those topics (Tully, 2006).

As will be shown in the following chapter, the energy-water context is yet far from being integrated into the various levels of governance, management and implementation of sustainable governance. Sustainable governance is a highly multifacted topic, with various overlapping key features as e.g. Rinaldi (2019)

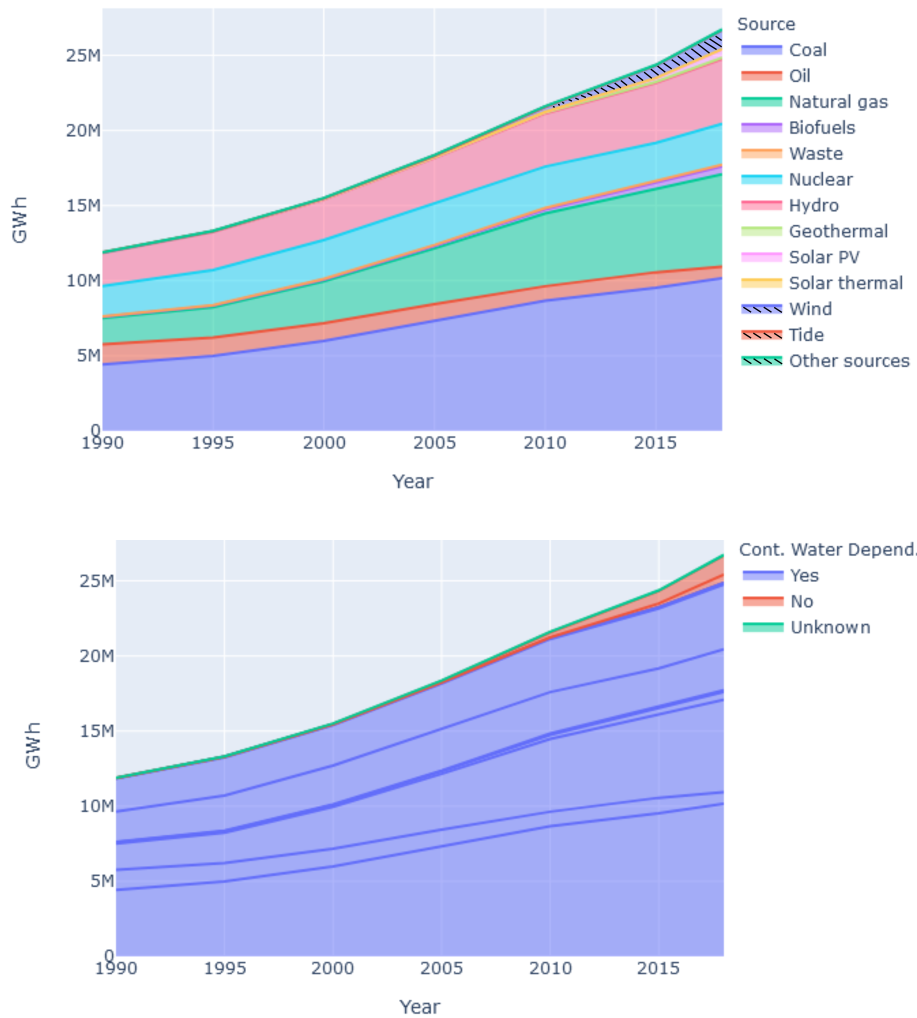

Figure 1.3: Global annual electricity generation according to International Energy Agency (2021a). The continuous water dependency does not differentiate between sea and fresh water, nor does it account for possible air cooling.

shows.

To understand the general concepts of sustainable governance, it is important to understand the advent of sustainability in governance and management and the impact it has as one of the potentially most powerful and ambitious supranational tools of human society: The Sustainable Development Goals (SDGs).

1.2 On the multifaceted character of sustainability

Sustainability is derived from the English verb *to sustain* and the most straightforward approach to have an immediate understanding for it is its linguistic definition, provided in this case by Oxford University Press (2021):

> *Sustain - To make something continue for some time without becoming less*
>
> Oxford University Press (2021)

To have a notion of what this means for the context of energy-water, a simple way is to insert key phrases, which translates the definition into:

> *To make* ***electricity generation*** *continue* ***with water*** *for some time without becoming less* ***electric energy or water***

Though the expression above demonstrates the basic principle of sustainability - to maintain the good/resource - it is a highly limited way to reflect on sustainability (and the energy-water context). However, in contemporary science and politics, the definition and genesis of sustainability are far from being explicit. Coming from a historic view, Purvis et al. (2019) points out that the whole emergence of sustainability has been accompanied by a lack of clarity.

Whilst having its roots already in the 1960s, the first introduction of sustainability on the public stage was made in 1980 by the UN (Purvis et al., 2019) with little global attention and just a vague definition. Just a few years later, the first works pointed out the multifaceted character of sustainability, among them Caldwell (1984) and O'Riordan (1985). But it was no earlier than 1987 when the Brundtland report was published (World Commission on Environment and Development, 1987), that the vibrant discussion about sustainability that stretches into every branch of the contemporary society, arose. It was this very report that gave *sustainability* its most infamous, yet by far not its only, definition.

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*
>
> World Commission on Environment and Development (1987)

Following the pattern of a simple key phrase insertion from above, the definition transforms into:

> ***Energy-water sustainability is sustainability*** *that meets the needs of the present without compromising the ability of future generations to meet their own needs* ***of electric energy and water***

This definition disengages water and energy from a mere quantitative perspective and makes room for holistic views. It emphasizes *abilities (...) to meet (...) needs* instead of a mere *becoming less*. However, the definition does not deliver many details that would support sustainable decision-making.

The concept of sustainability was decisively shaped by Barbier (1987) in the same year who identified a three pillar/circles/sphere model, which is roughly separated into a) an economic b) an environmental and c) a social dimension.

The existence of such sustainability dimensions in and around the energy-water context can be easily demonstrated with three simple questions for a hypothetical power plant site. It is emphasized that they are merely illustrative and far from being exhaustive or complete:

1. If water is scarce, should air be used as coolant for a thermal energy plant, although this makes the process less efficient and therefore much less *economically* sustainable?

2. Should the heated coolant water be disposed back into a river at temperature X, although this might exceed the tolerable temperature of riverine species, thus endangering *environmental* sustainability?

3. Should scarce water be abstracted for cooling, although the domestic and agricultural sector and *social* sustainability could be endangered?

Those are only three briefly touched issues. The highly complex energy-water interplay will be illuminated in detail in Chapter 2.

The three-dimensional view of sustainability was, though, regarded as simplified and under-theorized by critics in literature (Robinson, 2004; Purvis et al., 2019; Bali Swain, 2018). Subsequently, three main critics on the concept of sustainability are listed:

- It is not clear what each dimension frames exactly and what has to be understood by each of it (Robinson, 2004; Purvis et al., 2019; Bali Swain, 2018).

- It exists a fundamental debate of view that determines how sustainability can be assessed: Two mainstreams exist, out of which a) claims that the three dimensions are to be seen as a system approach for sustainability (all three of them need be be approached unitedly); versus the claim of b) that the three dimensions are different ways to view sustainability (i.e. that sustainability possesses three different fashions that cannot be united). (Bali Swain, 2018)

- It disputed whether the economic dimension really is necessary for sustainability. Its paradigm of continuous growth seems to contradict sustainability. Should it not be disintegrated and merged into the environmental and social dimension (Robinson, 2004; Bali Swain, 2018)?

Henceforth, the debate about sustainability has branched into many flows and sub-flows that were determined by different views, interpretations and disciplines. Consequently, various competing sustainability definitions were established (Robinson, 2004; Marshall and Toffel, 2005). The ambiguity reaches so far that many disciplines have their own vast flock of definitions. E.g. Moore et al. (2017) identified 24 variants of sustainability definitions in medicine. A main pro of this variety is flexibility to adapt to a manifold of different situations more or less individually, as the variety of disciplinary definitions demonstrates. The main con is that those differences might induce counterproductive sustainability assessments within, across and among disciplines (Robinson, 2004).

Most probably, there never will be a prevailing understanding on either sustainability or the borders of its dimensions. Although the three-dimensional character of sustainability is the nowadays dominating way of how sustainability is interpreted (Purvis et al., 2019), the existing variety to view on it makes joint and coordinated sustainable action a challenge.

Subsequently, Purvis et al. (2019) points out a "lack of rigor in the theoretical underpinning of sustainability" and a "difficulty in producing operational frameworks for the characterization of sustainability". Purvis et al. (2019) argues retrospectively that the unspecificity for a detailed, global understanding of sustainability ended up in an urge for clarity that introduced target and context based sustainability specifications - on a global scale - with the establishment of the United Nations' (UN) Sustainable Development Goals (SDGs) (United Nations, 2015; Caballero, 2016).

1.2.1 The Sustainable Development Goals

The SDGs are the result of a stepwise political process on an international level that is marked by the Brundtland report from 1987, the Rio declaration from 1992 and the Millenium Development Goals from 2000 (United Nations, 2015; Caballero, 2016). The process reflects the development from a rougher overarching concept to target-based approaches of sustainability.

The SDGs were ratified by the members of the UN in 2015. They consist of 17 different categories, i.e. goals. Each of the SDGs encompasses one, two or even three of the three dimensions described by Barbier (1987). Every goal consists of eight to 12 targets that incorporate one to four indicators.

The goals are manifold and wide ranged, reaching from *Peace* (SDG 1) over *Gender Equality* (SDG 5) to *Climate Action* (SDG 13). They also comprise *Clean Water and Sanitation* (SDG 6) and *Affordable and Clean Energy* (SDG 7). They thus incorporate both main elements of the energy-water context.

Each country is expected to meet each goal by 2030. However, the SDGs are non-binding (United Nations, 2015; Caballero, 2016; Bali Swain, 2018).

The SDGs are generally receiving broad approval (Barbier and Burgess, 2019; Bali Swain, 2018; Pradhan et al., 2017) as an important step on the macro level, that succeeded in framing 17 different sustainable definitions for specific problems that can be targeted on a global scale. Nonetheless, they are also subjected to three main critiques.

1. **A lack of action induction, scaling and communication** According to Easterly (2015), the answers that are supposed to be delivered by the SDGs do not help to establish direction or instruction to confront a concrete problem in reality. Purvis et al. (2019) emphasizes a lack of final rigor and detail, which would make policy application on the problem level difficult.

2. **A lack of responsibility identification**. The SDGs would not deliver any support in indicating who are the ones responsible to take action and interaction to initiate sustainability processes (Easterly, 2015).

3. **Inconsistencies between the targets**. Several targets are identified to have synergies and/or trade-offs (Nilsson et al., 2016; Zhang et al., 2016a; Barbier and Burgess, 2019). According to the critiques, the SDGs would not address cross-goal issues. This would create inconsistencies that inhibit the completion of the respective SDGs (Spaiser et al., 2017; Bali Swain, 2018; Barbier and Burgess, 2019).

The critiques are also valid for the SDGs regarding water (SDG 6) and energy (SDG 7) as a simple insight into their respective SDG indicators demonstrates: Energy is not mentioned once within the water (SDG 6) indicators. Vice versa, water is not mentioned once within the energy (SDG 7) indicators (Kickert and Press, 2016a,b).

Just one indicator of SDG 6 (6.4.2 - *Level of water stress: freshwater withdrawal as a proportion of available freshwater resource*) vaguely includes the question of energy dependency on water via water competition between various sectors (in this case domestic versus others, including electricity) (Kickert and Press, 2016a). SDG 7 is even less fleshed out in this respect, having no indicator that remotely addresses the energy-water context (Kickert and Press, 2016b). Moreover, the scale of SDG 6 and 7 is delimited to the country level and the indicators are of no instructive character. This fits to the findings of Bali Swain (2018), Easterly (2015) and Purvis et al. (2019) that the SDGs are not meant to work as an instruction criterion for sustainable action or as identification criteria to detect responsible persons to take action.

The SDGs are obviously meant to address the macro scale of and between states. The cross-SDG problem of the energy-water context, however, does apparently not act on that macro scale, as its failure to be included or addressed in the SDGs demonstrates. This delivers the research question of how the energy-water context is to be addressed:

> ***Q1.*** *What does a definition and assessment for the sustainability of the energy-water dependency for all electricity generation types look like?*

The question needs to be answered to address the pending issues of action, interaction and responsibility for problem solutions mentioned by Easterly

(2015) and Purvis et al. (2019). A sound identification and assessment of sustainability in its various dimensions for energy-water context on the right level allows stakeholders to act appropriately.

1.2.2 A Cross-SDG example: The Water-Energy-Food-Nexus

As it was demonstrated in Chapter 1.2.1 cross-SDG contexts are not well represented by the SDGs. Nilsson et al. (2016), Zhang et al. (2016a) and Barbier and Burgess (2019) show that SDGs cannot be regarded in an isolated manner. However, if so, cross-SDG topics cannot be separated from other issues (other SDG or cross-SDG topics), either. This holds also true for the energy-water question. A simple and swift proof of the embeddedness of the energy-water context in even vaster contexts is the so-called water-energy-food-nexus (WEF-Nexus).

The WEF-Nexus states that the preconditions for sufficient supply of each of its elements for human needs are the other two and that none of them can exist without the other (Simpson and Jewitt, 2019). The nexus was initially developed by hydrologists, researchers and practitioners from the water sector and later embraced by other disciplines. After it focused in its primary years strongly on the security aspect of the respective resources, it opened subsequently for different topics and different inter-dependencies (Pahl-Wostl, 2019). In the process, the general critique towards the WEF-Nexus formed around its vagrant character that was described as overlapping with other topics (Al-Saidi and Elagib, 2017; Liu et al., 2018) and being in parts arbitrary (Allouche et al., 2015).

The energy-water dependency is embedded by logic into the WEF-Nexus. It is moreover obvious from the contemporary debate that the nexus is embedded in or connected to other issues (other SDG or cross-SDG topics). This shows that a clear framing of a single problem is extremely difficult, especially when it comes to real on-site challenges. Indicators like those provided by the SDGs will not be able to reflect all aspects. The same would hold true for cross-SDG assessments. The fuzziness and inter-connectedness of sustainability topics is very high and the claim to reflect all connections must be weighted against the requirement to assess and to induce concrete action.

1.2.3 Security instead of Sustainability?

The Brundtland definition from Chapter 1.2 reinforces that sustainability is a task that encompasses generations. Sustainability is therefore long-term. If transferred to the energy-water dependency, it can be said that the energy-water issue is long-term as well. Thermal power plants and the electric grid are designed to generate electricity for decades. This is even more valid for hydro power reservoirs that are partially utilized for more than a hundred years and that are expected to last for some centuries more (Annandale, 2013; Schleiss et al., 2016; Kantoush and Sumi, 2017). Electricity generation thus fits into the sustainability pattern.

However, the context of energy-water goes beyond this long-term characteristic as the research of Berry et al. (2015) regarding *food sustainability* and *food security* demonstrates for the WEF-Nexus. Berry et al. (2015) argues via a thorough historical analysis that both security and sustainability share many attributes and that a clear separation is neither possible nor desirable. In his debate, he suggests that security must be integrated into the concept of sustainability. In this, security overlaps with many, but not all sustainability aspects, as security as such addresses an issue that sustainability might not be able to encompass: Immediateness.

The difference might appear trivial, but it is nonetheless impactful: When a concept called *security* regards immediate issues (i.e. immediate need of food (but also water or electricity)) it is automatically bound to on-site problem solutions and a non-macro (thus meso or micro) point of view. It thus treats crucial points of critique to *sustainability* made by Easterly (2015); Bali Swain (2018); Purvis et al. (2019). Without going into a more detailed analysis of security (this will be made in Chapter 2), sustainability and security can be - according to Berry et al. (2015) - distinguished in a subsequent manner: a) Sustainability: Long-term, macro; b) Security: Immediate, meso/micro.

Though proposed for food issues, the established WEF-Nexus allows to transfer the concept to water, energy and, logically, to energy-water contexts, since each component of WEF-Nexus conditions the other as shown in Chapter 1.2.2. Subsequently, the immediateness of food conditions the immediateness of energy and water.

It is hence valid to say that the energy-water context forms part of sustainability issues (as power plants are subject to decades or centuries of usage), but its constant need for immediateness (i.e. constant need of water, as electricity is to be supplied constantly) make it also subject to the security issues. The energy-water context is thus a question of energy-water security.

It is important to stress that, following the theorem of Berry et al. (2015), security does not neglect sustainability's long-term characteristics. As it is part of sustainability, the governance of e.g. the energy-water context must definitely be considered to be capable of maintaining functioning electricity generation in the future. For instance, hydro power reservoirs must be maintained working for the centuries to come. Security however, emphasises that the recipient of the security - i.e. in most cases human beings or a human society - will perish if security is not maintained immediately (or at least in the very immediate future).

Human beings will perish in the near future without a supply of food and the perishing is not avoided, if food will be maintained sustainable on a macro or long-term level. Likewise, a human meso or micro society (a region, a county, a village) will perish (from the dignity of a modern Anthropocene, so without any hospitals, communication systems or food supply chains working) without electricity. This does differentiate the SDGs 6 and 7 from other SDGs like SDG 12, *Responsible Consumption and Production*, or SDG 13, *Climate Action*. Human beings will not perish immediately, if SDG 12 or 13 are not be fulfilled immediately and on the micro scale. They eventually will do so in the long-term future and on macro scale, but not in the short-term.

Thus, *energy-water sustainability* makes sense and *climate sustainability* makes sense, too. Moreover, *energy-water security* does make sense, but *climate security* does not.

Subsequent, the research question from Chapter 1.2.1 must be slightly reformed.

> ***Q1.*** *What does a definition and assessment for the security of the energy-water dependency for all electricity generation types look like?*

1.2.4 Transference of concepts and the implementation of action

Immediateness demands action. Action and the identification of responsibility were, however, central critique points of sustainability (Easterly, 2015; Bali Swain, 2018; Purvis et al., 2019). The sustainability mindset encompasses security. The security perspective shifts the focus and prepares the theoretical ground for action against challenges in the energy-water context. However, the practical implementation of insights gained on the energy-water security macro level remains a crucial and not finally answered issue.

Pahl-Wostl (2019) remarks that "there is no widely accepted definition guiding its [the security's] application in (...) governance and policy" and that implementation of security/ sustainability concepts are indeed quite limited.

Some approaches or frameworks on implementation are promoted with higher emphasis, e.g. within the WEF-Nexus. What prevails regarding the transference of concepts and the implementation of actions is a diversity of security application theorems and concepts, demonstrated for instance by water security (Cook and Bakker, 2012; Pahl-Wostl et al., 2016). While this is regarded a strong setup against unspecific and thus non-sustainable panacea (one-solution-for-all-problem) solutions, it is also agreed that diversity induces non-negligible implementation strategies (Pahl-Wostl, 2019). While the debate about the style of implementation of security/ sustainability concepts into on-site challenges persists, it is agreed that the actual challenge is the lack of implementation as such (Pahl-Wostl, 2019).

Imbalances between stakeholders are a main inhibitor of the on-site implementation of security and sustainability concepts (Pahl-Wostl et al., 2013; Pahl-Wostl, 2019). This holds true for all three WEF-dimensions (McMichael, 2011; Zarfl et al., 2015) and thus for energy-water security, as well. Some stakeholder groups (potentially those with lack of power in the decision making processes) are not integrated in the process of decision making or their integration is just superficial. Their knowledge and opinion is thus not accessed in the process, which has deteriorating effects on on-site implementation of security and sustainability concepts (Faysse, 2015; Faysse et al., 2018; Silva et al., 2019) The missing participatory integration of stakeholder groups (without power in decision processes) is seen as one key factor in the perpetuation of the imbalance (de

Leal Filho and Brandli, 2016). From this, a central question for the energy-water context originates:

> ***Q2.*** *How to overcome stakeholder imbalances to transfer security aspects to on-site action in the energy-water context?*

1.2.5 The mindset of action in the energy-water context

Though it is constantly pondered how to induce the sustainable and security conformed action, one thing is certain: Action is already happening! But it is not (necessarily) sustainable action. The energy-water context is upon constant and immediate demand as demonstrated in Chapter 1.1 and also 1.2.3. Action has already been there before the ideas of sustainability and security gained popularity.

Large parts of the infrastructure for electricity generation have already been installed to enable humankind to leap into the Anthropocene. The chapters 1.1 and 1.1.5 demonstrated the contemporary dependency on the installations that already exist. This means that governance and management of this infrastructure are not just already enacted, but that they are already enacted under a certain mindset.

This mindset has been - desirable or not - formed and developed in the era of non-sustainability. This does not mean that management of that era did not act sustainably, but that sustainability as a concept had not been formed as a formulated and guiding idea. In accordance with Chapter 1.2, the era of non-sustainability thus can simply be called: the Pre-Brundtland era. It is necessary to know more about the Post- and Pre-Brundtland mindset in action and management in the energy-water context to retrieve two important parts of information about the energy-water infrastructure: a) Information about the setup of the prevailing, already existing, physical or organizational infrastructure b) Information about the present impact from sustainability and security thinking and thus the ((in)direct) consideration of the dependency of electric energy on water.

Long-term data and historical analysis on the sustainability mindset in the energy-water context are however scarce. Most knowledge is transferred via historical perspectives.

Steven Fawkes (2001, 2016) draws a picture of (electrical) energy management throughout the decades for the United Kingdom beginning in the 1970s. It is pointed out that prior to the oil crisis in 1973, monitoring, targeting and thus saving of energy was not a widespread or even common approach, and that the integration of energy generation into planned energy production matrices was far from being perceived as necessary. It is valid to say that long-term thinking did not appear to be in vogue. But without long-term thinking, there is no sustainability as demonstrated in Chapter 1.2.3. Though concepts of sustainability and energy security were introduced into science, society and industry in the 1980s, it became visible that the practical implementation of such ideas was overruled by other (economic) mindsets and hardly came into action before the

2000s (Steven Fawkes, 2001, 2016). A major inhibitor was yet again the lack of acting stakeholder involvement and persuasion (Bowonder, 1984; Suk et al., 2014; Blass et al., 2014; Schulze et al., 2016).

Cherp et al. (2017) demonstrates the different paths that Germany and Japan took in their electric generation policies, arguing about the influences of different mindsets in their energy transitions. Sometimes, seemingly more sustainable pathways were fueled by non-sustainable thinking, e.g. Germany's phase-out from nuclear energy that was (initially) strongly enforced by the coal industry. Cherp et al. (2017) emphasize that many governmental and management decisions were the result of non-coherent decisions of (strong) stakeholders (Cherp et al., 2017; Hake et al., 2015; Fouquet and Pearson, 2012).

The mindset of management and governance for the generation of electricity has been a continuous subject to constant influential change of potent actors with an (in parts erratic) response to new perspectives in society and science (Cherp et al., 2017; Cherp and Jewell, 2011; Fouquet and Pearson, 2012). Contemporary analysis regarding electric energy management (with more or less focus on water) normally frames the last two to three decades. Most often, those analyses do not focus on single management actions of front-end stakeholders or practitioners apart from case studies (Li et al., 2016; Gao and Glowacka, 2016; Macknick et al., 2012; Zhang et al., 2018b). It is thus very difficult to pinpoint a) a society's/an industry's exact mindset of management action regarding energy-water sustainability/security b) the exact effect of management action on sustainability/security for the context energy-water dependency, as data is scarce and difficult to interpret. For the energy-water context, this creates two central questions:

> ***Q3.*** *How to determine a sustainability/ security mindset in management action within the energy-water context?*

> ***Q4.*** *How to determine the sustainability/ security impact of single management actions for the energy-water context?*

1.3 From security to effect: The levels of the dissertation

The prior Chapter 1.1 demonstrated the (almost) inevitable dependency of water on energy and the formation of the so-called energy-water context. Chapter 1.2 showed that energy-water is indeed a cross-SDG topic that is affected by immediateness and thus belongs to the sustainability's macro sub-level of security. It is, however, unclear how the macro sub-level might be formed, defined, evaluated and indicated for energy-water.

A major point of critique for the sustainability/security concept was its lacking advice for on-site implementation. Thus it lacked transference of the macro to the micro level, which means that methodologies for the meso level transference are needed. This is also valid for the energy-water context.

As the energy-water context is already an infrastructure under implementation, it is important to know more about the meso mindset (and mindset transformation) of the current and historic way of implementation that determines the micro points of management action that are taken. It is important to see how far sustainability/ security concepts are reflected.

Eventually, on-site action is taken at the micro points of (management) action.

Those points of (management) action will have again an effect at a meso level, which determines the sustainability/ security of the energy-water infrastructure.

Figure 1.4 depicts the multi-leveled structure that precedes and follows a (management) point of action in the energy-water context.

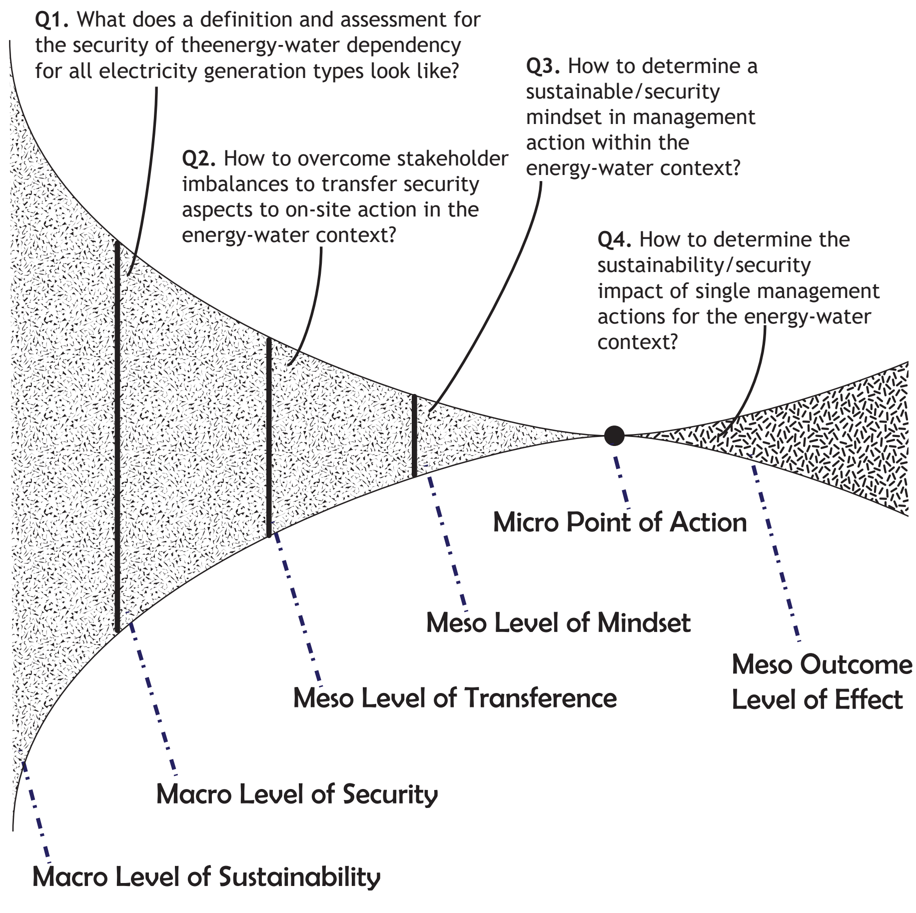

Figure 1.4: The levels that prevail and follow management action and the research questions for the energy-water context attached to them

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This dissertation will reflect on each of the four questions of the four addressed levels with a main chapter (in one occasion with two main chapters) that were or are about to be published as articles. However, as Chapter 1.1 has already indicated, each level is accompanied by a certain degree of lack of clarity, which is an inherent part of the scientific debate around sustainability, security and their application.

It is thus unlikely that the research presented in this dissertation will deliver immovable or 100%-clear responses to each of the questions. Rather, it will contribute pieces of well-grounded and carefully researched information that will be able to draw a clearer picture on the layered process that precedes and follows management actions in the energy-water context.

Various article types and research methodologies were chosen to deliver meaningful answers. They are depicted in Table 1.1.

Table 1.1: Articles to answer the dissertation's research questions

Question	Level	Article Type	Main Feature	Country	Region
Q1	Security	Methodologic Paper	Energy-Water Security Indicator Concept	Global	Unspecified region based
Q2	Transfer	Case Study	Strategy implentaton against verto-horizontal disconnect	Morocco	Middle Drâa Valley
Q3	Mindset	Original Research	Optimism Bias Detection in Reservoir Management	Japan	Japan
Q4	Effect	Original Research	Effect of Management Action for Reservoirs	Japan	Japan
		Case Study/ Original Research	Effect of Management Action for Reservoirs	Brazil	Ceará

Subsequently, a brief outline on the background of the articles will be drawn to deliver the necessary technical background for a more profound insight to the research of this dissertation.

1.3.1 Q1. A holistic energy-water security assessment

Chapter 1.2.1 demonstrated the inevitable inter-linkages of the energy-water context beyond both SDG 6 and 7 for water and energy, whilst Chapter 1.2.3 argued that security needs to act on a sub-national level. The SDGs were identified to not be capable (and not meant to be capable) of reflecting the energy-water context in a holistic and sub-national manner. Holism and sub-nationality are, nevertheless, demanded from the energy-water cross-SDG character as shown in Chapter 1.2.2 and 1.2.3.

Research, into how far an assessment system for the energy-water context is already existent and how far it copes with the necessities of security/ sustainability view, is thus mandatory.

The dissertation hence surveys existent assessment systems and builds upon its findings a tailored design for energy-water security assessment in case the delivered content of existing assessment systems is not congruent with the necessities of the security/ sustainability view.

The results will deliver answers to **Q1** and enable sub-national decision-makers to actively reflect and react on water dependency of electric energy generation. The assessment system to be delivered will enable users to detect synergies and trade-offs in the respective regions and to negotiate with the front-end inducers of management about action strategies that would aid in overcoming energy-water challenges.

The South Upper Egypt Region (SUER) will serve here as a swift, illustrational example with no claim to depict the real conditions in a sufficient and exhaustive manner. Egypt's high dependency on one river, the Nile, makes it a very good showcase.

Egypt's energy generation is almost entirely dependent on water, mainly due to thermal power plants. Roughly 10% (1990 more than 20%) of Egypt's energy generation depends on hydro power. The electricity from hydro power is generated by three reservoirs, all of which are situated in the South Upper Egypt Region (International Energy Agency, 2021b).

Especially the Aswan High Dam has importance as it forms Lake Nasser, whose water is in parts diverted for industry and agricultural purposes to the Toshka project. The Toshka project consists of several artificial lakes in a side valley depression of the Nile and is connected to the Lake Nasser via the Zayyid channel. Due to its location, high evaporation losses are projected. The project will officially be concluded in 2022 (Elsawwaf et al., 2014; Abd Ellah, 2020). A regional competition situation on a scarce freshwater resource thus exists between agriculture, industry, domestic uses and energy generation. The situation might put each of the sectors under pressure, i.e. insecurity depending on their respective development (and the region's population increase). In addition, the Great Ethiopian Renaissance Dam, which was concluded in 2020, is projected to influence water level variation of the Nile significantly. This further influences predictability and enforces energy-water purpose conflicts (Abd Ellah, 2020). The situation is illustrated in Figure 1.5

In case the regional administration decides to irrigate more desert land using Lake Nasser or to erect a water-dependent concentrated solar power plant (which would be an optimal location due to high radiation), assessment criteria that would indicate effects of electricity generation as well as water supply would be splendid. This would support decision-making. The assessment criteria ideally could holistically indicate (among other factors): a) the stability of the fresh water resource supply (that might be altered due to the freshly constructed upstream reservoir and climate change (Abd Ellah, 2020)) b) the sector competition pressure c) the already existing dependency of regional electricity generation on fresh water supply.

The results of this dissertation's research will deliver an assessment methodology for such cases. The research will produce a concept for a holistic and sub-national energy-water security assessment system. This would deliver a crucial response to research questions **Q1**.

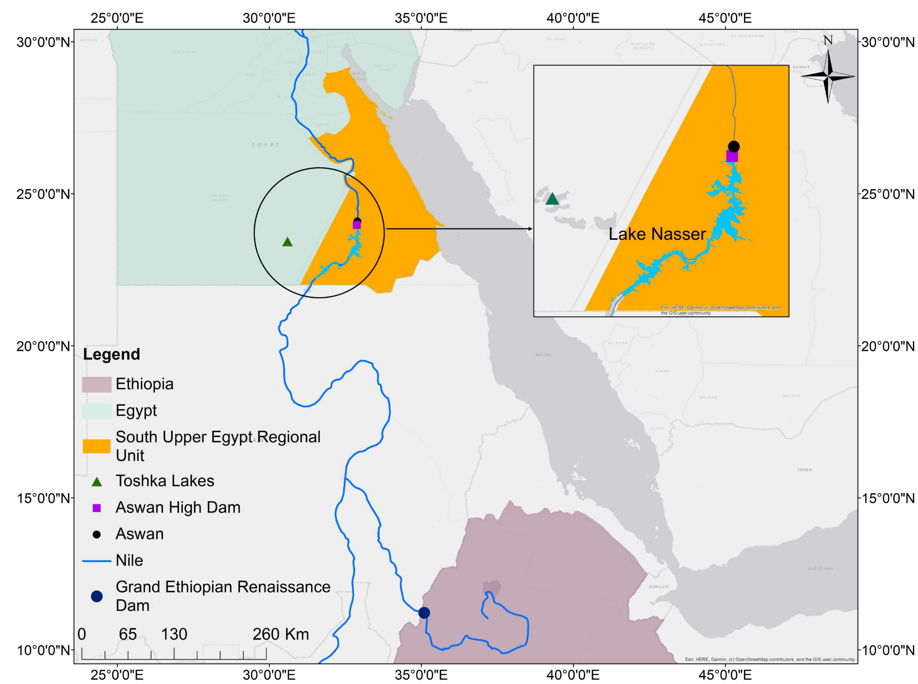

Figure 1.5: The various influence factors that impact water-energy security for the SUER in Egypt and the Aswan High Dam near the city of Aswan

1.3.2 Q2. A transference case study

The variety of socio-economic-ecologic environments for the energy-water context already becomes vivid upon changing the illustration landscape of the SUER from Chapter 1.3.1 into an apparently similar but yet different region, which is also located on the border of the vast Sahara desert: the Middle Drâa Valley (MDV) with its main city Ouarzazate in the region Drâa-Tafilalet in Morocco.

The similarities of the Middle Drâa Valley to the South Upper Egypt Region are obvious: Irradiation and average temperature are high, the weather is arid and most of the landscape is desert. Like in the SUER, the MDV agriculture and the domestic population have a one-river dependency on the Wadi Drâa, an ephemeral riverbed, which is formed as an outlet of the reservoir Mansour El Eddahbi. The reservoir itself is supplied by the rivers Dades and Asif n'Tidili/Asif Iriri as its - by far - main contributor. Their locations are displayed on the map of Figure 1.6. The Mansour El Eddahbi is the main water source for agriculture in the whole region, but also for domestic uses and electricity for the region. With the Noor project, one of the largest concentrated solar power plants on the globe was installed, and is partly cooled by the water of the Mansour El

Eddahbi (the rest of the power plant is air cooled) (Schinke et al., 2015).

The SUER conditions are apparently alike, but in detail quite different. The extent of the reservoirs and the differences of impactful grand scale projects (Noor vs. Toshka) are just two example parameters that already demand case-based transference of security concepts, even if the same assessment system (for energy-water dependency) would be used.

The Mansour El Eddahbi of the MDV was installed in 1972. This led to a rise in agricultural production. It also supported a rise in the domestic population and the tourism industry due to higher and more secure water availability (Heidecke et al., 2010). The Mansour El Eddahbi, however, suffers from the problem of sedimentation (see Chapter 1.4.2), which deprived it of at least half of its active storage capacity. While water supply has shrunk, WEF-demand and - more importantly - the degree of dependence on the reservoir, has risen (Diekkrüger et al., 2010).

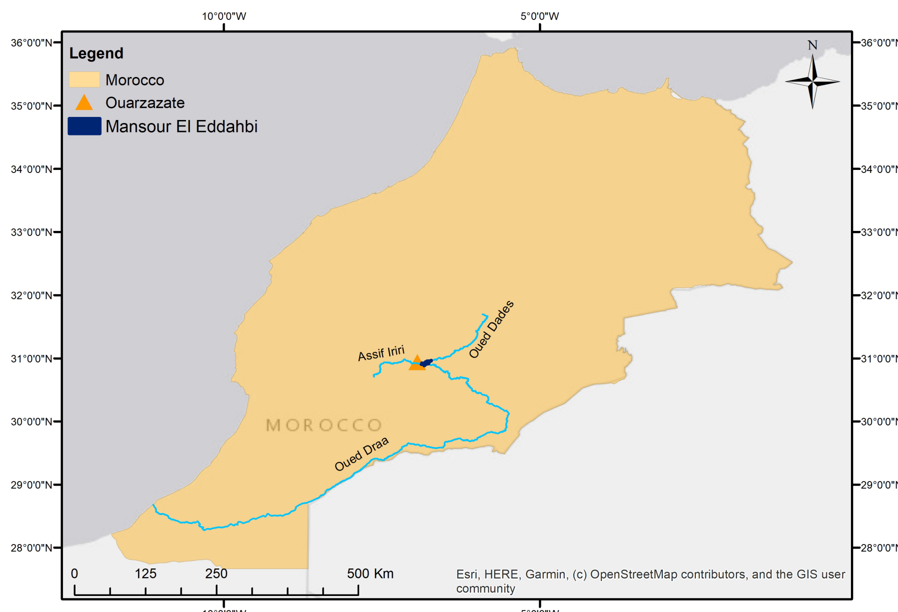

Figure 1.6: Ouarazazate, the Mansour El Eddahbi, the ephemeral Wadi Drâa and its main contributors in the MDV

Strategies to mitigate and/or amend the described kind of situation are already existent and have been developed by (Moroccan) governments, politicians, organizations or programs. The most famous among them is the Plan Morocco Vert, that is emphasized to follow sustainability principles and was developed on a national scale (Faysse, 2015; Bouzidi et al., 2020). The strategies are (in parts) scheduled and/or expected to be applied in the MDV.

There is thus an over-regional/national/international level that developed, evaluated and assessed the Moroccan/the MDV's WEF-challenges and their ideas ought to support decision-makers and those responsible for (management) action in the MDV.

The MDV environment was thus ideal to carry out a case study regarding the transfer of the macro sustainability/security level to the point of application. On the one hand, there are sustainability/security plans and strategies in action. On the other hand, on-site and not yet solved WEF-challenges are imminent and demand management action (Diekkrüger et al., 2010; Faysse, 2015).

Simultaneous to the development of the last years, governance research for various topics of the WEF-Nexus has already been conducted in the MDV region by the Wuppertal Institute (WI) (Schinke et al., 2015), a partnered institute of the University of Osnabrück. Due to this already existing professional connection, advantage for the dissertation's research could be taken: A research scenario (see Chapter 3) that corresponds to the meso level of transference (see Figure 1.4) was established in the MDV.

Regional/National level planners and strategists have thus been united in a workshop with on-site decision-makers and stakeholders from WEF-challenged sectors. They evaluated the obstacles, backgrounds and strategy opportunities for sustainability/ security action transference for the MDV. This delivered answers to research questions **Q2**. Especially in the Middle East North Africa (MENA) region, such research has been scarce (Al-Masri et al., 2019; Hoff et al., 2019) and thus, the insights gained from this dissertation's research to find answers to research questions **Q2** are particularly valuable.

1.3.3 Q3 and Q4. A global problem to study the mindset and effect of management action

The situation of the Mansour El Eddahbi (Diekkrüger et al., 2010) described in Chapter 1.3.2 is far from being a unique case. Annandale (2013) detected a global crisis for the sustainability and security of reservoirs caused by sedimentation. Millions of cubic meters of active reservoir storage have already been lost, which threatens both fresh water supply and electricity generation.

Reservoirs are an infrastructure measure that have already been in use for roughly a little more than a century (Annandale, 2013; Ansar et al., 2014) for various purposes, among them hydro power (Votruba and Broža, 1989). This means that management of the very concrete sedimentation problem in the energy-water context has already been happening under a certain mindset. Sedimentation management action has also had an effect for more than a century on the security and sustainability of electricity and water supply.

The issue of sedimentation of reservoirs in the energy-water context is therefore an ideal issue to be surveyed to answer the research questions **Q3** and **Q4**. Thus, an outstanding presence in this dissertation was appointed to the issue. The subsequent chapters will illuminate reservoirs and reservoir sedimentation to illustrate the background, need and aptitude to survey this very threat to the key infrastructure element of reservoirs in the light of the research questions **Q3** and **Q4**.

1.4 Reservoirs and reservoir sedimentation

Chapter 1.1.1 already briefly explained the basic principle of hydro power in reservoirs: The energy of water stored in its elevation is converted into electricity utilizing gravity as means of acceleration of the water to turn a turbine connected to a generator (Dixon and Hall, 2014). The task of reservoirs is, however, not restricted to electricity generation. They are multi-purpose infrastructure objects. Some major purposes of reservoirs are listed below (Votruba and Broža, 1989):

- Hydro power
- Flood control
- Drought control
- Public water supply
- Agricultural irrigation
- Mining
- Fishery
- Leisure and tourism

Therefore, the sedimentation of reservoir lakes is not only an issue that massively affects energy security, it also affects other fields of reservoir utilization, among them water and food supply (Votruba and Broža, 1989; Annandale, 2013). Reservoir sedimentation is therefore a prime example of WEF and sustainability complexity. Reservoirs, like all WEF and sustainability/security topics, are not isolated laboratories and isolated laboratory conditions can hardly simulate real world WEF conditions.

1.4.1 What determines a reservoir's storage size

Rivers are identified as the most sustainable source for reservoir usage. This has several reasons. One is the demand for fresh potable water for the reservoir's multi purpose. Another is the replenishment rate, which is roughly on the same level as the timescale of usage (days, weeks, months). Rivers give the opportunity to use the energy of water that is stored in the elevation difference of their basin slope. Those are advantages that make rivers apt as reservoir sites. Other sources of water (sea or groundwater) are comparatively unsuited (Annandale, 2013).

Reservoirs exist in many shapes, styles and storage sizes, built for manifold purpose compositions. All of those features are in decisive parts determined by the stored river(s). The subsequent focus of the chapter will be laid upon the factors that are crucial to determine the storage size. They are listed below and follow Annandale (2013), where more mathematical detail can be examined.

The below versions are slightly simplified by Annandale (2013), who for example left special evaporation cases aside.

- **Supply**. Defined as Mean Annual Flow (MAF) of a river.
- **Demand**. Defined as a fraction of the MAF considering all allotted consumers (nowadays also including. to a certain degree, environmental needs). Higher demand should lead to a bigger reservoir size (capped by supply maximum) for the sake of reliability.
- **Variability**. Extremes of annual MAFs of a river, often expressed as a standard deviation of annual flow divided by MAF. Higher variability will raise the necessity of reservoir size to guarantee reliability.
- **Reliability**. Years during which fresh-water can be reliably supplied, divided by years under consideration. If the hydro power part of the reservoir demands for 99% reliability, that means that the reservoir is meant to 100% supply the water demand of the hydro power plant needs during 99% of the years. In the remaining 1% years, less than 100% may be supplied. The measure is time-based.

The listed factors were mathematically determined and empirically conformed. This leads to the frequently used (reviewed) Gould-Dincer methodology (Gould, 1964; McMahon et al., 2007), which is represented by Figure 1.7. It is a crucial piece of information for design of reservoir storage size.

The graph illustrates the optimal storage size of a reservoir based upon the MAF and in dependency of river variation and yield (demand versus supply). E.g. in the case of a demand of 50% of the river supply at a low variance of 0.2 with requirement of a 99% reliability, a run-of-river application would be suitable. This means that neither a dam nor a reservoir would be needed (or they must be of a very small design).

Figure 1.7 now demonstrates intriguingly, which kind of impact environmental (e.g. climatological, topographical etc.) conditions can have on the reservoir size. In case the same reservoir (50% of demand, 99% reliability) would be erected in a semi-arid area with a rainfall and a dry period (i.e. in Spain or northeast Brazil), this would elevate the river flow variation massively, e.g. to 0.6. Now, a reservoir is recommended that would have to encompass roughly half of the MAF size - instead of an (almost) non-reservoir run-of-river solution.

It is obvious that it is extremely important to know both data for the river flow and data that determine the (future) demand upon constructing a reservoir. Wrong or incomplete data are thus a big challenge for short- to mid-term supply security and long-term sustainability.

There are several influencing factors that have a negative effect on reservoir security and long-term usage. Management needs to constantly react to initially unforeseen (or ignored or underestimated) conditions (like the erection of upstream dams or climate change in the SUER case (Abd Ellah, 2020) or strong sedimentation of the MDV case study (Diekkrüger et al., 2010)). The

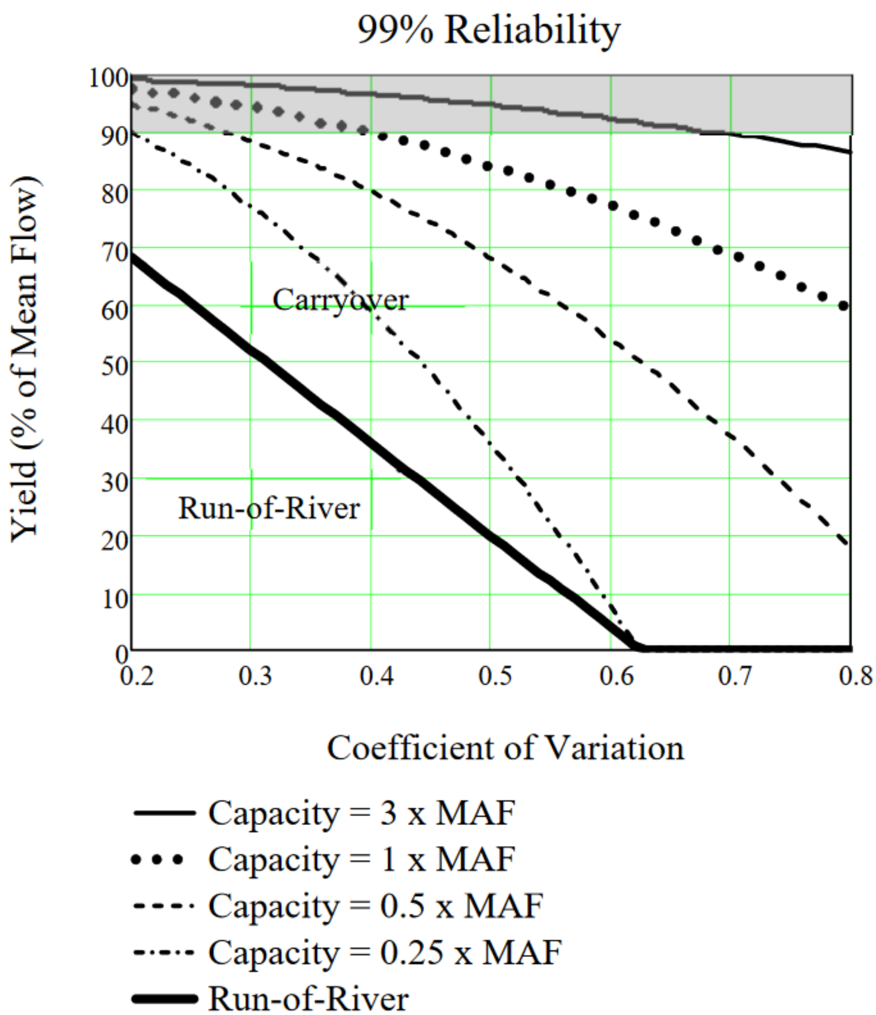

Figure 1.7: Storage size design for a reservoir based on MAF, river flow variability at 99% reliability according to McMahon et al. (2007) and illustrated by Annandale (2013)

main adversary in this process is sedimentation, which is also denominated as siltation (Morris and Fan, 1998; Annandale, 2013). Unfortunately, though, data for sedimentation gained via monitoring is scarce.

1.4.2 Sedimentation

Rivers work as a conveyor belt for every type of earth material, be it clay, silt or sand. Depending on the force of the river, even gravel and stone may be dislodged, either being dragged or washed away (Morris and Fan, 1998). Every river transports a certain amount of material that eventually stops being conveyed in the case that a river loses the force it exerts. This happens when the flow velocity diminishes. Reservoirs are such flow velocity diminishers. Subsequently, sediment tends to precipitate at great quantities in reservoirs (Morris and Fan, 1998; Morris, 2020).

The accumulated sediment eventually blocks the storage size of the reservoir. It literally reduces its capacity to supply all the water that is demanded according to its initial design.

The Brune curve in Figure 1.8 is an empirical measure to assess sedimentation in reservoirs, established already for a long time in reservoir design (Brune, 1953). It demonstrates the high conflict potential that exists between reservoir supply security, indicated in Figure 1.7, and sedimentation.

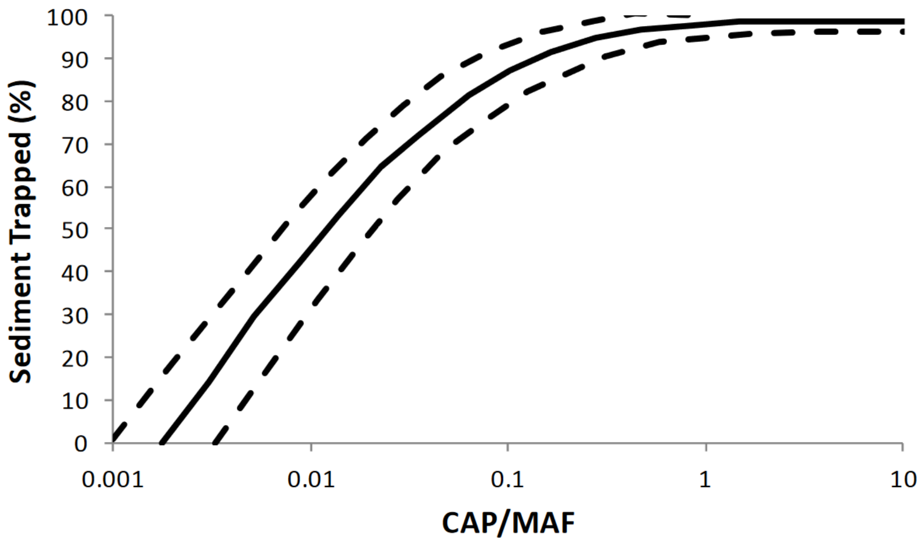

Figure 1.8: Sedimentation rate in relation to reservoir capacity (CAP) versus MAF according to Brune (1953) and illustrated by Annandale (2013)

Reservoirs, whose capacity surpasses 10% of their rivers' MAF, will already accumulate 80% of the rivers' sediment load. However, almost all reservoirs need to surpass the 10% of MAF limit. Consequently, most rivers on the globe are heavily affected by reservoir sedimentation for the sake of short/mid-term security. If left untouched, sedimentation will, however, occupy the storage size of the reservoir, reducing its capacity to be long-term secure, i.e. sustainable.

For the reservoir's purposes, this has tremendous consequences. This also affects hydro power.

Hydro power is one of the most efficient electricity generation technologies. This is (also) due to the fact that it needs to convert energy one time less than thermal power plants (no heat to kinetic; in thermal power plants, the heat is used to vaporize water that again will spin a turbine (Sarkar, 2015a)). Every conversion means the loss of energy transference efficiency due to non-ideal processes. Moreover, the hydro power technology is quite advanced thanks to more than a century of development. E.g. the frequently utilized Francis turbines for hydro power can reach an astounding conversion efficiency of up to 95% (Dixon and Hall, 2014).

The technical principles of a hydro power plant are not touched directly by the sedimentation: The turbine uses the fall height of the water within the dam to be spun. Hydro power works hence more or less like a waterfall - and storage is theoretically not needed. The rotating turbine is connected to a generator which induces via electromagnetic fields an adjacent current in a conductor (Dixon and Hall, 2014). Ignoring mechanical and electromagnetic losses, hydro power converts kinetic energy more or less seamlessly to electric energy.

Sedimentation will, however, literally affect the hydro power's security/ sustainability. It reduces the active storage space (Annandale, 2013; Kantoush and Sumi, 2010), which is the reservoir's security asset against droughts, i.e. the MAF variance. As soon as the inflow river MAF variance increases (e.g. due to climate change) and the initially installed storage does not correspond any more with the initially projected demand, the hydro power's reliability is about to be endangered.

Supposing that a hydro power reservoir's storage size is initially planned to guarantee five years of hydro power operation during drought. If after 25 years 40% of the active reservoir storage should be silted, the reservoir will only be capable of maintaining operation on the designed level for three years. Hence, the aimed reliability is missed.

This gets even worse if one reflects that the MAF variability is generally on the rise due to climate change (van Vliet et al., 2013; Flörke et al., 2018) or upstream river dams (Grill et al., 2015; Abd Ellah, 2020). This might mean that the drought that is to be expected will last six or even seven years and not the originally planned five. The reliability of hydro power and thus the water-dependent energy security is threatened.

The dramatic effect of sedimentation becomes visible with a look at the overall active storage capacity of reservoirs: It has been shrinking since the 2000s (and in the per capita case since the 1980s) (Annandale, 2013). The problem is moreover about to multiply since reservoir construction experiences a new high (Zarfl et al., 2015). In case sedimentation is not part of the management mindset of such reservoirs, fierce sustainability problems are to be expected for hydro power supply. Sedimentation management is thus a mandatory issue for reservoir security and sustainability.

1.4.3 The Optimism Bias - An influential mindset in reservoir management?

Based on the situation described in Chapter 1.4.2 it is necessary to determine the mindset behind reservoir construction.

It is important to note at this point that management measurements that (help to) balance the sedimentation inflow and outflow have been existent for quite a time already (Morris and Fan, 1998; Sumi and Kantoush, 2011; Kantoush and Sumi, 2017; Morris, 2020). They are crucial tools to form energy-water security in reservoirs and long-time sustainability. Given their long-known character it must be assumed that those techniques were known to planners, managers, engineers and operators at all times. Moreover, it must be assumed that they are, and were, well aware at all times about the long-time character of reservoirs. Reservoirs were thus assumed to be secure and sustainable by planners, managers, engineers and operators. And they had to be confident about this.

Confidence in their own capabilities regarding the original reservoir design and the anti-sedimentation measures play a great role in infrastructure management. However, this confidence is known to be the subject of a great bias issue, called *Optimism Bias* (Kahneman and Tversky, 1979; Kahneman, 2011; Flyvbjerg, 2016). Optimism bias leads to the (un)conscious overestimation of the own (skilled) capabilities, the underestimation of challenges (in this case sedimentation for security and sustainability) and the non-incorporation of so-called *Unknown Unknowns* (Kahneman, 2011; Ansar et al., 2014): Events that ought to be incorporated by extra risk margins. An example is the intensification of the MAF variation due to climate change.

An optimistically biased (management) implementation of the long-term energy-water infrastructure element "reservoir" is an important evidence that the sustainability/ security thinking from the macro-level has not yet reached the meso level of implementation for whatever conscious or unconscious reasons. To wit, a reduction of optimism bias reservoir sediment management would be the increased recognition of its long-term effects on security and sustainability. As reservoirs have (theoretically) a century-long record for sedimentation management, reservoir sedimentation would be a supreme example to study both the mindset in which action is taken and the effect of the taken action for the energy-water context.

Kahneman (2011) and Ansar et al. (2014) propose the so-called *Outside View* that is generated via a so-called *Reference Class* as measure to detect the optimism bias. The methodology is, however, dependent on large data amounts. As sedimentation is a complex and non-linear process (Morris and Fan, 1998; Morris, 2020), the mere reliance on the Brune curve from Figure 1.8 is not sufficient. The Brune curve might be theoretically helpful, but it does not account for all the individual events (upstream dams, heavy rain catastrophes or human land use change, among many impact factors) that impact on siltation (Morris and Fan, 1998; Morris, 2020). The most convenient way to derive statements about the optimism bias and the sedimentation management mindset and effect would be existent data from monitoring. A large data set and complex analytical tools would therefore be necessary.

1.4.4 Japan and Brazil: Origins of reservoir data

Reservoir sedimentation is a process that is difficult to monitor, as it eludes the human eye and perception for three reasons: a) it is a submersing process, b) its origins are of microscopic size, c) it is a long-term process on the scale of years and decades.

Thus, monitoring of sedimentation, which forms part of bathymetry, demands high quality technical equipment, skilled technical capability and a high degree of long-term organization (Balan et al., 2013; Adebayo Olubukola et al., 2020; Kumari and Ramesh, 2020). Though reservoirs are a worldwide applied infrastructure element (Annandale, 2013; Zarfl et al., 2015), it becomes evident that only a minority of countries have the capability to conduct long-term monitoring that might help in answering **Q3** and **Q4** of the research question (Morris and Fan, 1998; Annandale, 2013).

Japan is one of the exceptions (Sumi and Kantoush, 2011; Kondolf et al., 2014; Auel et al., 2016). The country's administration succeeded in generating a vast data set for the siltation in more than 1000 reservoirs that were constructed over a vast period of time, beginning in the 1900s. Japan allows hence to draw a picture on optimism bias in sediment management and on the mindset and effect of management action in the energy-water context throughout a century.

The country's data pool was hence identified to be ideally suited to help to find answers for **Q3** and **Q4** via selected analytical methodologies. As a counterpoint, the Brazilian region of Ceará has been chosen to check for the transferability of the methodology to a less favorable, but more commune, data situation. As Ceará almost encompasses an equally long reservoir construction history (the first large reservoir was constructed in 1906) with very distinct social, environmental and economical conditions, its analysis is seen as ideal enhancement of this dissertation's research (de Araujo et al., 2006). Both regions, Ceará and Japan, are illustrated in Figure 1.9.

The complexity of such non-linear data demands for a highly skilled analytic methodology, which this dissertation found in Artificial Neural Networks (ANNs) (Schmidhuber, 2014; Michelucci, 2018). They were used as a crucial instrument to derive responses from the mentioned data to answer **Q3** and **Q4**.

1.5 Artificial Neural Networks

Even in case a long record of data has been carefully monitored and collected, analytical methods to evaluate those were limited by the complexity of the data and the lack of computational power to extract information. Questions like the ones about the mindset/optimism bias in management action against reservoir sedimentation and the effect of said management action were issues that could hardly be answered based on data for a long time.

For the vast majority of conscious human evolution, humanity just knew one physical structure that was capable of solving such highly complex problems: the human brain, which creates (or at least frames) the human mind. Hence

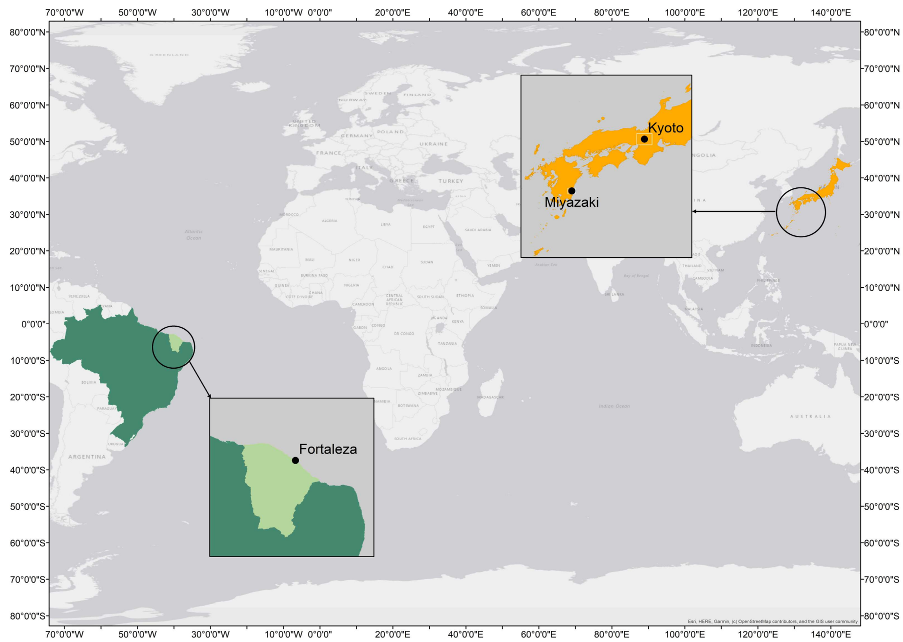

Figure 1.9: Japan and Ceará in Brazil, alongside the cities of Mizayaki, Kyoto and Fortaleza, the locations of the universities where the main research for the Chapters 4 to 6 was conducted

it was no surprise that once the human brain's internal systematic was roughly identified, scientists tried to mimic its structural conditions to find solutions to complex problems (Fox and Franz, 1987).

McCulloch and Pitts (1943) were the first to actively try imitating the neural structure of the human brain, whilst Hebb (1949) established important theoretical foundations to do so. Later on Rosenblatt (1958) developed upon their works a so-called *Perceptron*, that was improved by Minsky and Papert (1969) into a weighted structure. It was called an *artificial neuron* and is displayed in Figure 1.10.

Figure 1.10 demonstrates that the neuron which executes a mathematical function $f()$ takes up inputs X_i that are weighted with weights W_i. The results of $f()$ are continuously skewed by a sigmoid activation function that helps to decide whether the neuron's output R' will lead to any further action (i.e. by surpassing an arbitrary threshold value).

Such neurons were combinable and could thus support the search for complex answers. This marked the creation of the first Artificial Neural Networks (ANN). The principles of that early epoch are still in use today.

After initial success of the structure, the scientific community recognized

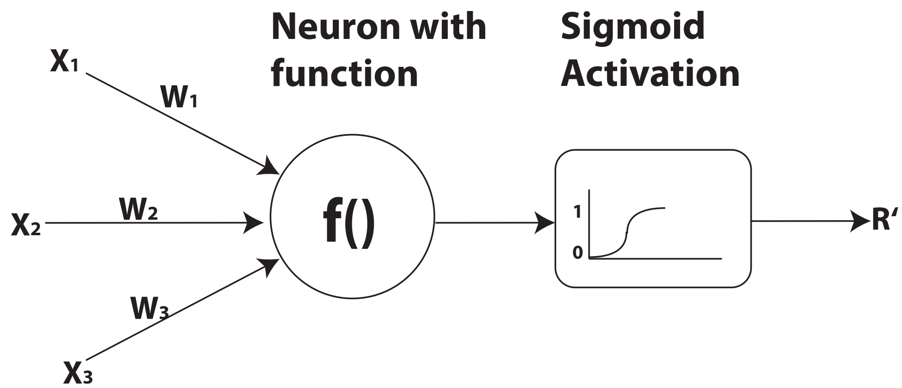

Figure 1.10: A classical Minsky-Papert perceptron with sigmoid activation, inputs X_i, output R' and weights W_i

(with the study of Minsky and Papert (1969)) at the end of the 1960s a major drawback of the ANN methodology: Computation resources and their calculation time. Due to their structure, neural networks are bound to iterate through an infamously large number of simple mathematical operations. However, in the 1960s, such operations took longer to be executed than nowadays. Today's transistor based micro computer chip technology was still far from finding its way into everyday life. Computers were, compared to today, slow, bulky and prohibitively expensive. ANN operations would occupy those computers for months or years or even more time. Hence, ANN development was generally left aside as it was deemed impractical for real life, or even scientific operation.

1.5.1 The Multilayer Perceptron

Nevertheless, important research steps for ANN technology were still being made. Werbos (1975) introduced the famous principle of *Backpropagation*, which enabled ANN-engineers to develop the, until today, most important feature of ANNs: Learning.

If a result R of a relationship is known, the perceptron's output R' can be compared with R. The deviation between R' and R determines subsequently the so-called *Loss*, which updates the weights, in order to come closer with R' to R in the next iteration, when the inputs X_i are fed again to the perceptron.

Later on, Rumelhart and McClelland (1987) introduced the so-called *Connectionism*, a principle which mimicked the neural structure of the brain in a more appropriate way. The connectionism was adapted for ANNs and induced the principle of layered structures. This gave rise to the *Multilayer Perceptron (MLP)*. An example of a theoretical and simplified MLP with backpropagation is displayed in Figure 1.11.

Enhanced by thousands or even billions of neurons, an MLP like the one in

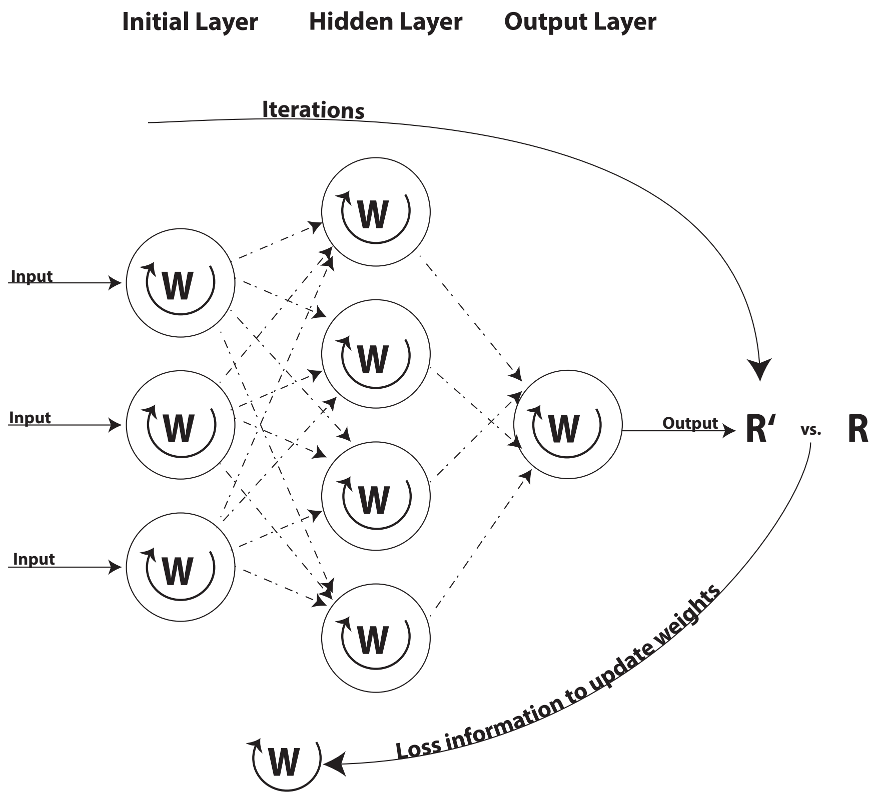

Figure 1.11: A simple, three-layered MLP with backpropagation. The weights are summarized by W.

Figure 1.11 is able to learn and adapt to highly complex non-linear relationships.

The strength of such an MLP is that it is able to *generalize*. This means that it does not merely copy linkages of the learned relationship. For instance, a network might be fed with the RGB (Red-Green-Blue) translated values of the pixels that represent cats on digital images. Be it so, then the network learns on 100 cat images. The task for the network is to recognize that the image shows a cat. It is a highly complex, non-linear task.

A well-trained network with the capability to generalize is not just able to tell that the 100 images on which it learned shows cats. A generalized network is able to tell the user even on unknown pictures (with a completely unknown cat to the network) whether the picture contains a cat or not. A well trained ANN is hence able to transfer its learned relationships to unknown data and conditions. This is a massive advantage if one needs to determine crucial, highly non-linear patterns within a data structure (like in the sedimentation case).

Of course a simple small network like the one of Figure 1.11 is nowhere close to complete such a task. It needs far more complex functions to realize this.

What was especially needed is computing capability to run networks with a vast size of neuronal connections for multiple times. This computing capability was achieved in recent decades.

Transistors (or better, micro-transistors) are the technical basement of computation. They are the physical representatives of computers' binary language (i.e. the 1s and 0s). Between 2000 and 2019 the transistor count on computational and graphical computing units (CPUs and GPUs) rose from 10^7 to 10^{10}, which is a staggering 100.000% (Sun et al., 2020). Though this is by far not all, the sheer improvement of transistor numbers during the last 20 years shows the avalanche-like speeding-up of the industry.

The last two decades thus marked a breakthrough for the ANN methodology(Chellapilla et al., 2006). A sufficiently large number of perceptrons are nowadays programmable and executable to approach complex non-linear problems with mass data. Due to the amount of computed neurons and the necessary CPU/GPU power, the ANN method is described as a brute force approach (Perez, 2017) or reinforcement learning (Zhang et al., 2018a).

Another breakthrough for ANNs is the availability of massive quantities of data (just the number of downloadable pictures is staggering). This is, however, just true in a reduced version for sedimentation data. Though the amount of sedimentation data for reservoirs in Japan is enormous for sedimentation research (Annandale, 2013; Schleiss et al., 2016), it is just fairly enough to work with ANNs. Fortunately, advanced and approved augmentation techniques are able to cope with this restriction in a statistically well-grounded way (more on this in Chapter 4 and 5).

1.5.2 ANNs as a methodology to reflect generalized sedimentation

The hypothesis of this dissertation's research is now that parameters can be found within the sedimentation data that reflect both the mindset (i.e. the optimism bias) and the effect of management action regarding reservoir sedimentation and on which ANNs can be generalized.

As the ANNs would generalize, they would not just merely copy the conditions of a certain reservoir (or a certain group of reservoirs) but actively include the internal variance and the different sediment behaviors in reservoirs that are caused by their different (environmental, topographical, social, demand etc.) characteristics. The parameters learned by an ANN could then be isolated, interpreted and evaluated.

An ANN trained on such data would thus represent the collected (data) experience of an entire region (in this case Japan and Ceará). Achieved results would therefore have an extremely high general significance, which is ideally suited to deliver answers within the energy-water context to the research questions **Q3** and **Q4** of this dissertation.

1.6 Outline

The following chapters are dedicated to the research questions, which were formulated and incorporated into the pathway of sustainability and security concepts to management action in the energy-water context during Chapter 1.2. They represent studies which are submitted to, or already accepted by, a peer-review publication process. The chapters reflect the energy-water context's process from the macro level of sustainability and security over the meso levels of transference and mindset over the micro point of action to the meso level of outcome, depicted by Figure 1.4.

Chapter 2 refers to **Q1** and approaches the dependence of electrical energy generation on water supply in all its generation-type variety. It defines energy-water security and holistically surveys the various types of energy-water interdependence via extensive literature research. Based upon the findings, an assessment set for energy-water security is developed that allows practitioners to thoroughly assess the various aspects of energy-water security for a respective region. Chapter 2 thus displays an important concept for energy-water context assessment and serves as origin for the development of sustainable and secure management strategy development.

Chapter 3 refers to **Q2** and surveys about the transference of strategy integration to management action for on-site WEF-challenges on the case study of the MDV in Morocco. The research identifies a main obstacle of strategy transference, namely the verto-horizontal disconnect: It is a stakeholder disconnect between front-end administrators, citizens and higher level administrations that inhibits the integration of strategies in reality. The research demonstrates that the verto-horizontal disconnect can be partially overcome by participatory and pragmatic approaches, namely public action situation encounters. Such an encounter was realized on a workshop and extensively evaluated via questionnaires, emergence and statistical methodologies.

Chapter 4 refers to **Q3** and investigates the mindset behind management action in energy-water context via a survey on the optimism bias (see Chapter 1.4.3) prevalent in sediment management of Japanese reservoirs. A sedimentation data set is created and methodology and decision criteria elaborated that support the detection of the non-sustainable optimism bias. Different networks of the ANN methodology presented in Chapter 5.2.2 were utilized to survey for the optimism bias.

Chapter 5 refers to **Q4** and surveys the effect of management action on security and sustainability for the energy-water context based upon the effect of anti-sediment management action in Japanese reservoirs. The sedimentation data set of Chapter 5 is very much enhanced compared to Chapter 4. A methodology to identify and extract information of management action from the data set is developed. A key element is Gated Recurrent Units (GRUs), a special neuronal operation for ANNs that allow them to actively suppress or foster data information of time series processes and thus include a memory function, were utilized to filter the effect of management actions on sedimentation from other data.

Chapter 6 also refers to **Q4** and investigates again for the effect of management action on the energy-water context. Again, the effects of management action on reservoir sedimentation is surveyed, however in Ceará, Brazil. Another, far less extensive data set than in Chapter 4 or 5 is set up. Different from Chapter 5 the effect of a specific management action is surveyed, namely the one of seasonal spilling (Sangramento). The amount of effect is determined via a numerical model that computes the water yield and simulates the water balance in the reservoirs using a Monte Carlos synthetically-generated inflow series (de Araujo et al., 2006). It is emphasized that the numerical modelling and thus the larger part (60-65%, a subjective guess) of the research was executed by the research partners. However, with the permission of the research partners, the research was integrated into this dissertation to give an illustration of the effect of a sole, concrete management action.

The dissertation thus operates going from the very broad macro level to the meso, almost the micro level, to survey the integration of sustainability and security into management action in the energy-water context. Chapter 7 summarizes the results. Furthermore, it provides a rather broad discussion on the implications and limitations of the studies presented in this dissertation. Finally, it gives an outlook on possible future studies related to the research presented in this dissertation.

CHAPTER

2

A HOLISTIC AND GLOBALLY APPLICABLE INDICATION SYSTEM FOR REGIONAL ELECTRIC-ENERGY-WATER SECURITY

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Abstract

The seventeen Sustainable Development Goals (SDGs) were designed to lead the modern Anthropocene to a lifestyle that was demanded by the Brundtland commission. Their objective is a common good that does not exploit the planet's environment and is thus long-term. Though virtually separated, contemporary research shows that the seventeen SDGs are intertwined. This is also the case for water and energy (SDG 6 and 7). The present research offers the first holistic indicator set that is designed to demonstrate the synergies and trade-offs between electrical energy generation and necessary water supply. It is founded on the SDG principles, follows a mindset based on the security definition established by Grey and Sadoff and is designed around the various technical dependencies of electrical energy and water. The set endeavors to reflect the manifoldness by which electrical energy is dependent on water supply in a dynamic ecologic, economic and social environment. As electrical energy and water interactions are identified for a regional level, the set is designed to be applicable on any administrative or basin area with moderate data availability. Thereby, the set includes industrializing and non-industrialized countries. It is based on six main indicators and sixteen sub indicators and seen as conceptual design for further discussion before application. The present paper argues and presents how those indicators are formed, why they are need, how and why they should be applied and why it is necessary if not inevitable to design cross-SDG indicators in a holistic view.

2.1 Introduction

The Sustainable Development Goals (SDGs) were developed as successors to the Millennium Development Goals (United Nations, 2015). They are designed in a holistic manner, meaning they are meant for the whole international community, and were ratified in 2015 by the United Nations (UN) and proposed to be reached in 2030 (Caballero, 2016). Currently, they are the pinnacle of mankind's endeavour to create a more sustainable future, as defined by the Brundtland Commission (World Commission on Environment and Development, 1987).

Seventeen SDGs were formed, each dedicated to a different global challenge. Research has demonstrated, however, that these seventeen SDGs cannot be regarded in a completely separated and secluded manner. Several synergies and trade-offs exist among them; they are intertwined (Pradhan et al., 2017; Nilsson et al., 2016; Jaramillo et al., 2019; Barbier and Burgess, 2019).

This also includes SDG 6 (United Nations Development Program, 2018), which is associated with the supply of water, and SDG 7(United Nations Development Program, 2018), which is associated with the supply of energy, as described by Nilsson et al. (2016) or Pradhan et al. (2017), who identified more than 1000 correlations in the forms of synergies and trade-offs between SDGs 6 and 7. Their interconnectedness is also part of the focus of the water-energy(-food) Nexus (WE/WEF Nexus) (Hamiche et al., 2016; Behrens et al., 2017; Flörke et al., 2018).

As Berry et al. (2015) shows for the food component of the WEF-Nexus, sustainability definitions get replaced by security definitions, as an *immediate need* exists to secure survival of human beings or human society in the near future. Sustainability would not reflect this according to Berry et al. (2015), as it is long-term. Since energy and water are inseparably connected to food via the WEF-nexus (Behrens et al., 2017; Hamiche et al., 2016; Flörke et al., 2018), the same conditions are assumed for all of the nexus components and thus, security will be used in most occasions instead of sustainability in the upcoming chapters.

A key target of the SDGs is to monitor the 17 different objectives in a scientifically valid way that meets the objectives outlined in the Brundtland report (Caballero, 2016). Systems for monitoring and assessing the goals are hence necessary. There is also a need for indicators that address the complexity associated with the aforementioned undeniable interconnectedness between the different SDGs, including the intertwined SDGs 6 and 7.

As shown in later Chapter 2.2.2, an assessment gap exists since contemporary indicating systems do not suffice in assessing the holistic nature between SDGs 6 and 7. Thus, corresponding indicators are designed as a conceptual proposal to further discussion and close the gap.

The present paper will treat *energy* in a homologous manner to *electric energy* or *electricity*. This will be reasoned in Chapter 2.2.1.

2.2 Contemporary State of Indication Systems

2.2.1 The Connection between Energy and Water

Energy and water are coupled via various direct and indirect means (Hamiche et al., 2016). Water is used as a coolant in Rankine cycle processes (Winterbone and Turan, 2015), as a driving force in hydropower plants (Zarfl et al., 2015) and as a prerequisite for biomass-based energy systems (Jans et al., 2018; Flörke et al., 2018). Conversely, energy is a key requirement for comprehensive water supplies due to pumping (Bolognesi et al., 2014) and desalination (Jones et al., 2019).

Global electrical energy generation has increased tremendously. In 2017, it quadrupled compared to the level in 1971 (International Energy Agency, 2019). In contrast, global water consumption "just"doubled in the same time frame (Wada and Bierkens, 2014). Due to recent developments (electric mobility(Klettke et al., 2018), the handheld gadget revolution(Morley et al., 2018), economic rise of the east(Sharvini et al., 2018) etc.), the electrical energy dependency is likely to continue its steep rise. Research forecasts that electrical energy generation will replace fossil energy generation in the middle or long term, especially in the field of mobility (Kåberger, 2018; Lepoutre et al., 2019; Homm et al., 2020). Based on this observation, the focus of the present paper is on the dependency of electrical energy generation (herein referred to as *energy generation*) on the water supply. This paper thus excludes the fields of mobility and energy generation that are directly powered by fossil fuels (e.g., calefaction). Moreover, the reciprocal dependency of the water supply on electrical energy is excluded for simplicity.

2.2.2 Necessity of a Energy-Water Indicator Set

Surprisingly, assessment systems that provide insights into the manifold interconnections between energy generation and water availability are rather scant. The dependence of energy on water is not even pointed out specifically within the recent reports of the International Energy Agency (2018) (IEA). Assessment systems that offer tools to solely monitor either SDG 6 or 7 are, in contrast, plentiful.

For SDG 6, assessment systems exist for different scales and purposes (Rickwood and Carr, 2007; Klümper et al., 2017; Jensen and Wu, 2018; Gassert et al., 2015; WWF, 2018). None of these sets attribute major attention to the energy-water linkage.

The sheer number of assessment systems for SDG 7 is even more overwhelming (Sovacool and Mukherjee, 2011; Standring and Mehlum, 2017; Löschel et al., 2010; Taylor et al., 2017). However, again, none of these indicating systems links energy consumption to water availability with major emphasis. The *energy security set* of the IEA does not even mention the dependency of energy on the inevitable demand for cooling water (Jewell, 2011).

Recent research demonstrates that an energy-water indication approach is indeed uncommon (Aboelnga, 2018; Markantonis et al., 2019). This includes the methods or indication sets used by important key organisations like the IEA (International Energy Agency, 2018; Jewell, 2011) and crucial controlling NGOs like the World Wide Fund for Nature (WWF, 2018). Further, it can be assumed that the relation between SDGs 6 and 7 has not received significant public attention, nor has it been a key focus in (political) infrastructure decision-making processes. Therefore, a specific assessment system with corresponding indicators is needed.

One of the few existing attempts to create an energy-water assessment system was initiated by the World Bank via the Thirst Energy Initiative. It rose awareness of the energy-water connection by carrying out several case studies. Nevertheless, a clear tool that monitors and evaluates the energy-water relation has not been introduced (World Bank, 2018).

Another initiative, namely, the Water for Energy Framework (W4EF), which was jointly initiated by the World Energy Forum, the World Water Forum and the Electricité de France (EDF), produced what is, to the authors'knowledge, the only energy-water-related set of indicators that is of a high impact (Lemoine and Bellet, 2015b).

The W4EF is indeed suited to give an impression of risks at the local level, especially in regard to quantitative water consumption conflicts between power plants and the immediate ecological and human environments. As such, the W4EF is a worthwhile tool.

Nevertheless, some issues are not addressed in a satisfying, i.e., holistic, manner, namely:

- **Governmental aspects** that reflect the capability of a country, region or municipality to set up and execute directives that harmonize the energy-water demands of different stakeholders. Research demonstrates that technical progress cannot be executed without a suited governance approach for its implementation, especially for infrastructural challenges such as the interconnected SDGs 6 and 7 (Pahl-Wostl, 2015; Kaufmann, 2005; Knieper and Pahl-Wostl, 2016; Daniell and Kay, 2017).

- **Capacity and economy restrictions** associated with spaciotemporal finite resources such as water (Rhoades, 1995; Rogers et al., 2002)

- **Long distance and long-term effects** that disrupt natural equilibria caused by the energy-based water demand (Zarfl et al., 2015; Grill et al., 2015; Annandale, 2013)

- **Differing scales**. The W4EF acts locally. A holistic approach demands, however, another scale. Many holistic interdependencies of SDGs 6 and 7 reside at regional levels because they are of physical/environmental (Liu, 2015; Abbott et al., 2019) or technical/political (Platzer et al., 2016; De Stefano and Garrick, 2018; Chazournes, 2009) natures. E.g. Liu (2015) and Abbott et al. (2019) emphasize the differences in regional basin conditions (that might be modified by human interference), that differ from semi-arid to tropical conditions and influence wide stretches of neither local, nor national nor global land. On the other hand, technical projects (Platzer et al., 2016) and (federal) political decisions (De Stefano and Garrick, 2018; Chazournes, 2009) have wide consequences for sub-national, non-local patches of nations. The local character of the W4EF is not capable of assessing those conditions.

A new, holistic assessment system is thus needed and is proposed in the present paper. An illustrative example might the South Upper Egypt Region (SUER). The region has a high hydro power production with the Nile being subject to high climatic and human made impacts (new upstream dams like the Great Ethiopian Renaissance Dam), which induces a completely new flooding pattern to the Upper Nile. The dams, especially the Aswan High Dam, of the South Upper Egypt Region themselves have a tremendous impact on the riverine system, whilst the competition situation for the water is high due to rising population and the agricultural Toshka project: Moreover, the introduction of photovoltaics and (maybe) water consuming concentrated solar power plants is discussed (Elsawwaf et al., 2014; Abd Ellah, 2020). The situation is illustrated by the map of Figure 2.1.

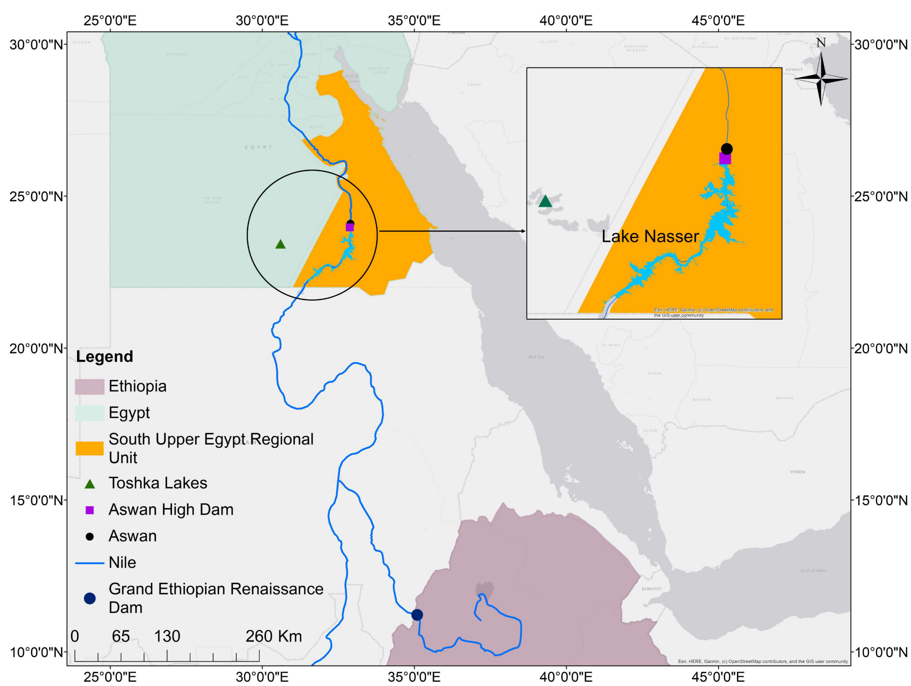

Figure 2.1: The various influence factors that impact water-energy security for the SUER in Egypt and the Aswan High Dam near the city of Aswan

The W4EF would give no indication to politicians, managers and operators, in how far dangerous supply and competition situations exist for the South Upper Egypt Region and whether new electric power plants might worsen or improve the water dependence situation.

Of course, this does not mean that the W4EF is an insufficient assessment system. Quite the contrary, it is apt for local analyses and as a non-governmental approach.

The system presented here will be another, more holistic alternative to the W4EF, and the framework deemed more useful by a given user will depends on the intentions of that user.

2.3 Conceptual Foundation and Methodology

The design of the system of indicators is dependent on a sound conceptual framework that provides the proper basis and guidelines. In this paper, the concept of risk avoidance, i.e., security, is used as a foundation. The prime criteria for the definition of security is the holistic approach, which is close to the intentions of the SDGs (Caballero, 2016).

2.3.1 Security in the Context of Electrical Energy and Water

The fields of science and economy have produced an abundance of definitions concerning energy and water security. All of these definitions address different types of risks and linkages with differing intensities.

For instance, there exist at least 38 definitions of energy security, according to a previous study (Winzer, 2012). Sometimes, these definitions focus strictly on efficiency aspects (IEA, 2019); sometimes, they incorporate the interconnectedness of energy and other factors (Laponche and Tillerson, 2001).

A similar observation can be made for water security definitions. Sometimes, water supply efficiency is the focus (Camapana, 2011); at other times, the interconnected aspects of water and other resources define the characteristics of the definitions (Grey and Sadoff, 2007).

The given variety displays two main orientations in the vast field of security definitions: a technical focus on one extreme, that allows preciseness; and a focus on interconnection on the other extreme, that facilitates decision-making processes. Of course, there are many nuanced security definitions between these two extremes.

2.3.2 A Joint Definition of Security for the Reliance of Electrical Energy on Water

Adding another definition to an already abundant pool of definitions cannot be regarded as efficient. Thus, the utilization of an existing definition as the foundation for the assessment system is deemed appropriate.

International Water Security Network (2018) screened several highly renowned definitions of water security regarding their holistic potential. International Water Security Network (2018) used several key topics as the means of comparison, as shown in Figure 2.1.

Table 2.1: Comparison of several water security definitions(International Water Security Network, 2018)

Definitions of Water Secuirty											
Source	Date	Livelihoods	Quality	Quantity	Health	Sust.Develop.	Ecosysems	Risk	Price	Global Change	Conciseness
GWP	2000	x	x	x	x	x	x				
Grey & Sadoff	2007	x	x	x	x	x	x	x			x
UNESCO	2008					x	x	x			x
UN WATER	2013	x	x	x	x	x	x	x	x		
OECD	2013		x	x	x	x	x	x			x
ADBO	2013	x	x	x	x	x	x	x			
Scott, et al.	2013	x	x	x	x	x	x			x	x

According to the International Water Security Network (2018), the Grey-Sadoff Definition is the most holistic. Its original version reads as follows:

> *Water security refers to the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies.*

It incorporates all categories except for *Price* or *Global Change*. Arguably, even those categories might be included, as some excerpts from the definition show.

Grey and Sadoff (2007)'s ”*acceptable quantity for livelihoods and economies*” implies an *acceptable price* that allows to receive an *acceptable quantity* of water. Moreover, *water-related risks* could include *Global Change*, as global change has long been known to include water-related risks (Vorosmarty et al., 2000).

The Grey-Sadoff definition therefore represents a broad holistic definition of water security. This offers the opportunity to adapt this definition to a cross-SDG-6-7 approach via enhancement. To do so, the desired characteristics of the enhancement have to be ascertained. The enhancement is based on three observations:

1. The vast majority of electrical energy (>90%) (International Energy Agency, 2018) constantly rely on water via the Rankine cycle, hydropower or biomass production (Winterbone and Turan, 2015; Zarfl et al., 2015; Jans et al., 2018; Flörke et al., 2018). It can thus be assumed that electrical energy is constantly dependent on water.

2. Energy generation causes feedback effects on water resources, which cause manifold constraints (Behrens et al., 2017; Flörke et al., 2018; Sanje, 2018). This, again, affects electrical energy production via its dependency on the

water supply (Hunt et al., 2018; Chico Zamanillo et al., 2017; Sumi, 2015). Thus, energy generation causes a water supply-based feedback loop on itself.

3. Energy generation and water supply are subject to administration and legislation, that determine the performances of both (Pahl-Wostl, 2015; Van de Graaf and Colgan, 2016)

These three observations lead to the enhancement (in bold) of the Grey-Sadoff Definition below:

> ***Joint energy and water*** *security refers to* ***a legally and administratively conditioned system with*** *an acceptable* ***availability of both interdependent resources*** *in a quantitative and* ***- in the case of water -*** *qualitative manner to ensure health, livelihoods and production, coupled with an acceptable and* ***circularly interlinked*** *level of related risks to people, environments and economies.*

The definition and observations can be translated into Figure 2.2.

The modified Grey-Sadoff definition implies that security for both energy and water can only be reached if their mutual relation is explicitly addressed.

According to the modified statement of Grey and Sadoff (2007), energy-water security is susceptible to various constraints, be it due to the quality or quantity of the resources or to risks of various dimensions. The circular nature of the energy-water connection is a key point here, as it implies that the constraints are not unilateral, but that, indeed, feedback effects, i.e., feedback constraints, exist.

It is important to emphasize the holistic nature of the definition. The quality, quantity and risks of the resources are not mere chemical or physical numbers but are subject to various aspects such as health (Ziolkowska and Peterson, 2016; Slorach et al., 2020), livelihoods (Ziolkowska and Peterson, 2016; Flörke et al., 2018; Kinoshita, 2012), production (Bridge et al., 2018; Flörke et al., 2018; Kinoshita, 2012), people (Cronin et al., 2018; Swyngedouw and McNeill, 2016; Ozkahraman, 2017; Pahl-Wostl, 2015), environments (Bridge et al., 2018; Ziolkowska and Peterson, 2016; Grill et al., 2015), economies (Bridge et al., 2018; Ziolkowska and Peterson, 2016; Hunt et al., 2018).

2.4 Main Indicators and Scale of Application

The identified energy-water relation from Chapter 2.3.2 allows the classification of the main areas of the energy-water interaction. These interactions have the potential to compromise energy-water security via qualitative, quantitative or risk-driven factors.

The main areas of interaction were identified using the modified Grey-Sadoff Definition and thorough research of the literature. In the subsequent list, key papers (which in part also cover the main aspects of the Grey-Sadoff definition; compare with Chapter 2.3.2) that support the identified main areas are quoted:

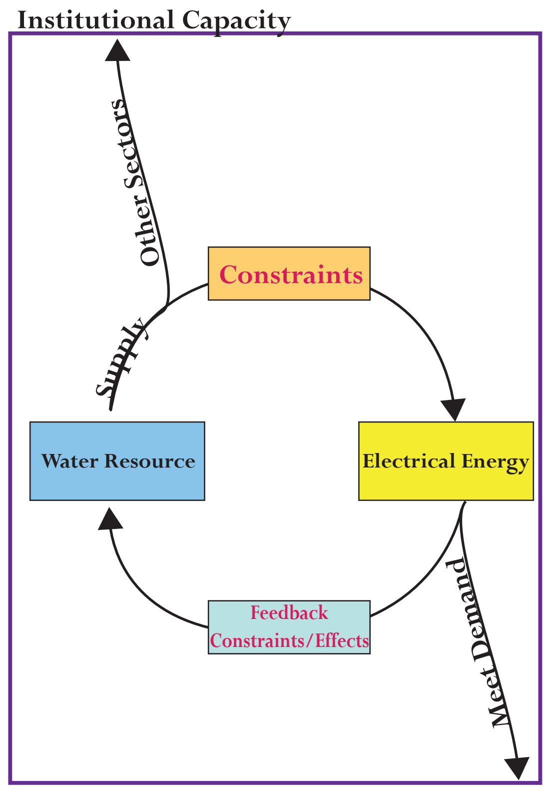

Figure 2.2: The interdependent energy-water relation, framed by legal and administrative institutional capacities.

1. Competition (Rhoades, 1995; Solow, 2008; Hunt, 2011; Ziolkowska and Peterson, 2016).
2. Constraints (van Vliet et al., 2013; Flörke et al., 2018).
3. Dependency (International Energy Agency, 2018; Bolognesi et al., 2014; Hunt et al., 2018).
4. Feedback constraints (Grill et al., 2015; Kedra and Wiejaczka, 2018).
5. Institutional capacity (Pahl-Wostl, 2015; Van de Graaf and Colgan, 2016).

The identified aspects serve as key areas in which investigations regarding the energy-water relation can be conducted. Their relation is depicted via a modification of Figure 2.2, shown in Figure 2.3.

Although the modified Grey-Sadoff definition and Figure 2.3 incorporate a holistic picture, the energy-water relation is not yet exhaustively described, owing to the necessary scale of the assessment area.

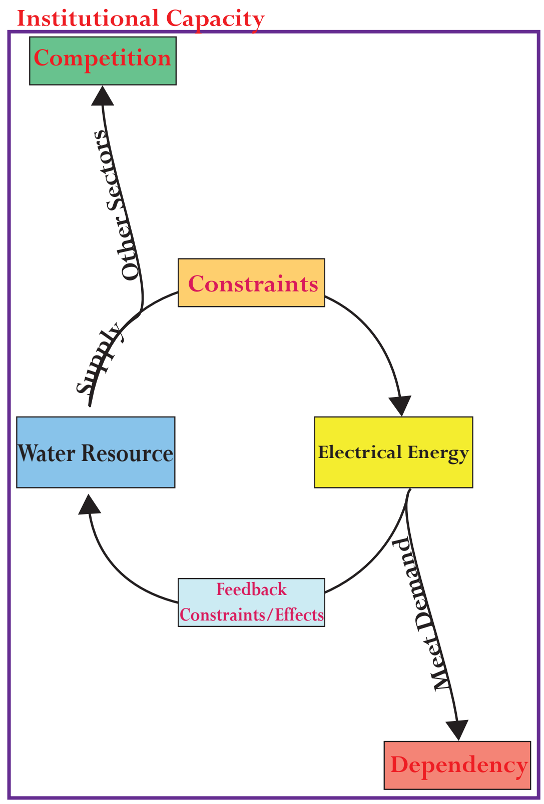

Figure 2.3: The main areas of the energy-water interaction that have the potential to compromise the security of the resources (in red).

The present paper regards the regional scale as the only valid and viable entity for a holistic energy-water security indication. The validity and viability of a region are reasoned as follows:

- *Validity.* Holistic interdependencies of SDGs 6 and 7 exist, especially at the regional level, due to physical/natural (Liu, 2015; Abbott et al., 2019) or technical/political (Platzer et al., 2016; De Stefano and Garrick, 2018; Chazournes, 2009) interactions.

- *Viability* The availability of data in many countries is restricted. Quite frequently, the most detailed level of available data is regional (or just national).

The definition *region* can be applied for both hydrologically (e.g., basin or subbasin) and administratively (e.g., province or state) delineated areas.

Per the definition from Chapter 2.2.1 all energy generation sites within the respective region are surveyed. However, this does not mean that all the water resources on which the energy sites depend will lay within the region. Water resources might need to be imported to satisfy the existing demand. To incorporate this transregional dependency, the concept of the water footprint (Hoekstra, 2017) is introduced. It serves as an equivalent supplement to the already-identified main aspects of energy-water security reduction. Hence, the list of main aspects is modified:

1. Competition (Rhoades, 1995; Solow, 2008; Hunt, 2011).
2. Constraints (van Vliet et al., 2013; Flörke et al., 2018).
3. Dependencies (International Energy Agency, 2018; Bolognesi et al., 2014).
4. Water Footprint (Hoekstra, 2017; Schomberg, 2020)
5. Feedback Constraints (Grill et al., 2015; Kedra and Wiejaczka, 2018).
6. Institutional Capacity (Pahl-Wostl, 2015; Van de Graaf and Colgan, 2016).

These main aspects are key features for the assessment of the energy-water relation and serve as the main indicators.

2.5 The need for Sub-Indicators

The main indicators listed above are coarse theoretical concepts that need specific sub-definitions or sub-indicators to be capable of serving in substantial quantitative evaluations. These sub-indicators are needed to allow an objective assessment.

For the purpose of sub-indicators, an enhancement of the relations depicted in Figure 2.3 was mandatory and was carried out via extensive literature research, which centred on a) the various types of energy generation; b) the Grey-Sadoff definition's key elements, i.e., quantity, quality and risks, in their various dimensions, as pointed out in Chapter 2.3.2; and c) aspects of regionality, as described in Chapter 2.4. Figure 2.4 demonstrates the key findings.

Figure 2.4 also indicates the positions and points of measurement of the diverse sub-indicators. Altogether, there are 16 of them. It is important to emphasize that the boundaries between different main indicators are fluid. For example, heat is both a feedback constraint of power generation (on the ecosystem of the aquatic environment) and a constraint for power generation (due to efficiency and legal limitations), as described in Chapter 2.6.2. The sub-indicator for the heat constraint thus might be applied in both the *Constraint* and *Feedback Effect* main indicators. In such cases, the initial definition of the research focus of this paper is referred to, i.e., that the effect of water resources on energy generation is mainly surveyed. In the case of the heat example, this implies that heat is seen as a constraint on energy generation.

Table 2.2 represents the affiliation of the sub-indicators to the main indicators and includes the main aspects that are covered by each sub-indicator within the corresponding main indicator. The full description and derivation of each sub-indicator is found in Chapter 2.5.2.

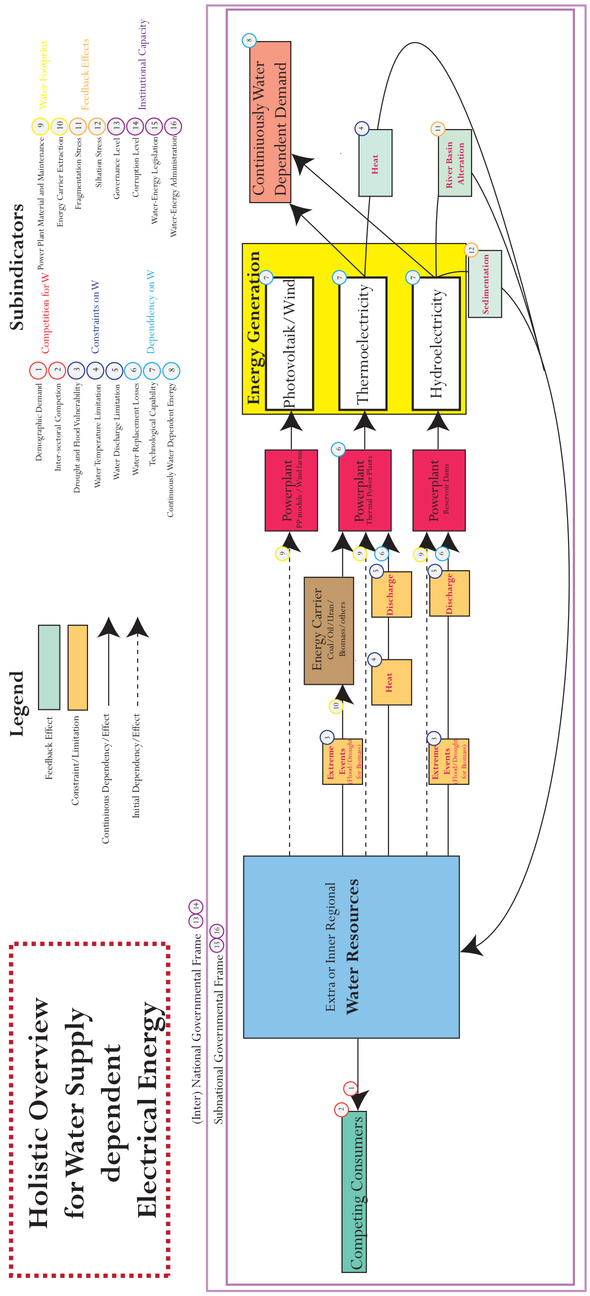

Figure 2.4: The holistic dependencies of electrical energy on water supply determined by the means of electrical energy generation types

Table 2.2: A brief overview of main and sub indicators

Main Indicator	Sub-Indicator	What is measured?
Consumption of Water	**Demographic Demand**	Rising population's water consumption with respect to the available water resources
	Inter-Sectoral Competition	Competitional pressure of the sectors on each other with respect to the available water resources
Constraints due to Water	**Drought and Flood Vulnerability**	Intensification of Flooding/Dryness events that hazard biomass production and available water resourcess
	Water Discharge Limitation	Riverine discharge/river height variety that hazards power plant cooling and reservoirs
	Water Temperature Limitation	Riverine temperature variety that hazards power plant cooling and riverine ecology
Dependence on Water	**Continuously Water-Dependent Energy**	Fraction of energy generation of a region that is continuously dependent on water
	Water Replacement Losses	Energy efficiency loss in case of transition to water-independent air cooling
	Technological Capability	Proxy to measure the capability of a society to become independent from Water-Dependent energy generation
Water Footprint	**Power Plant Material and Maintenance**	Water Footprint that measures the water consumption of power plant material with respect to the available water resources in the region of origin
	Energy Carrier Extraction	Water Footprint that measures energy carrier (oil, uranium etc.) water consumption with respect to the available water resources in the region of origin
Feedback Effects	**Fragmentation Stress**	Proxy to measure the impact of reservoir-based river basin alteration on the environment/the society
	Siltation Stress	Proxy to measure the longevity/sustainability of reservoirs and their impact on riverine flow equilibrium
Institutional Capacity	**Governance Level**	Measurement of a country's capability to react to the energy-water challenges
	Corruption Level	Measurement of a country's corruption level to also include non-Weber countries
	Water-Energy Legislation	Approach to measure a region's legislative capability to react to the energy-water challenges
	Water-Energy Administration	Approach to measure a region's administrative capability to react to the energy-water challenges

2.5.1 Aggregation System of Main and Sub-Indicators

The sub-indicators are evaluated individually at five levels. *Five* reflects situations of extreme risk, meaning that the energy-water security is extremely reduced. *One* depicts the very opposite. The principle is demonstrated in Table 2.3.

This range of levels provides enough lucidity for easy understanding but refrains from too much simplification (as would have been the case with three levels). It is thus a reasonable degree of levelling. The odd number allows the range to have a medium value, i.e., a barely acceptable condition.

The scores of the sub-indicators are fused arithmetically for each main indicator to obtain the respective main indicator's score.

In the case that certain sub-indicator data cannot be collected, the aggregation is subject to proportional weighting. If, for an instance, one out of two sub-indicators is missing , the obtained main indicator's weight is penalized, i.e., reduced, by 50%.

Table 2.3: The classification principle

Rating	Degree of Risk Potential
5	Extreme
4	Tremendous
3	Considerable
2	Perceptible
1	Unremarkable

2.5.2 Description and Derivation of Sub Indicators

As depicted in Figure 2.4 the energy-water relation succumbs to highly holistic interactions. The classification and quantification of such interactions that are, more than often not, clearly framed is a highly challenging process. The criteria by which this process was carried out are stated in Chapter 2.5. The following definitions of the sub-indicators are, however, not to be seen as deterministic but as a reasoned out and detailed concept that is open to further modification and discussion. A graphical rework of the main and sub-indicators is given in Figure 2.5.

2.6 Sub-Indicators

2.6.1 Consumption of Water

The consumption of a resource cannot be detached from its overall availability or from the different consumers that seek access to the resource (Solow, 2008); this is especially true if viewed in the light of sustainability (Hunt, 2011). All competitively induced risks are directly or indirectly related to the amount of and relation between the consumers (Ziolkowska and Peterson, 2016).

Demographic Pressure on Water Resources

The availability and allocation of fresh water is absolutely crucial for a society. It is no coincidence that humankind's first major civilizations were heavily reliant on supreme water management (Mithen, 2010). A region cannot always foresee its own population growth or, thus, a raise in its water consumption. Occasionally, this converts regions that were once water-secure into places with high water insecurity (McDonald et al., 2014), which is especially true for conglomerations of high urban growth areas (United Nations Population Division,

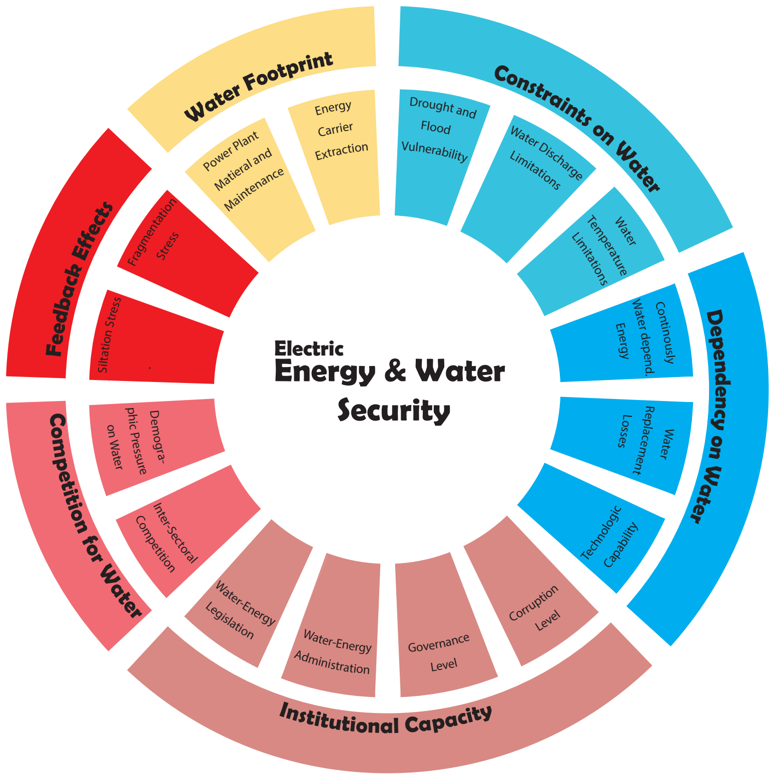

Figure 2.5: Overview about the energy-water indicator system

Table 2.4: Consumption of Water Sub-Indicators; DPW: Demographic Pressure on Water Resources; ICI: Inter-Sectoral Competition Indicator

Rating	DPW Rating	ICI Rating
5	DPW > 0.98	1.5 > ICI > -1.5
4	0.98 > DPW > 0.9	4 > ICI > 1.5 *or* -4 < ICI < -1.5
3	0.9 > DPW > 0.8	6 > ICI > 4 *or* -6 < ICI < -4
2	0.8 > DPW > 0.65	7 > ICI > 6 *or* -7 < ICI < -6
1	DPW < 0.65	ICI > 7 *or* ICI < -7

2014). In such regions, power plants are more prone to experience heavy water constraints. Therefore, an evaluation of whether and to what extent the future growth of a society will put a region under potential water and energy stress is crucial.

Conclusions on the internal demographic pressure of a region on water resources can be drawn if the environmental requirements, per capita water consumption data and water withdrawal from industry and agriculture are incorporated. Moreover, extra-regional populations that are dependent on intraregional water resources need to be considered.

$$DPW = \frac{PG * PFC}{TRR - EFR - FW} \tag{2.1}$$

DPW = Demographic Pressure on Water Resources
PG = Population Growth in Absolute Numbers
PFC = (Projected) Population Fresh Water Consumption per Capita
TRR = Total Renewable Water Resources
EFR = Environmental Flow Requirements
FW = (Projected) Freshwater Withdrawal by Agriculture/Industries

The development is evaluated in a simplified approach via a first- or second-degree regression extrapolated on AQUASTAT (FAO, 2019), Pacific Insitute(The Pacific Institute, 2019), WaterGAP (Grill et al., 2015), UN (which have proven to be quite reliable (Keilman, 1998)), AWARE (Boulay et al., 2018; Boulay and Pfister, 2013) or regional data with a *business as usual* assumption. The scoring assumes that a certain DPW buffer is needed to avoid risk.

In the case that a region needs to import water to quantitatively suffice its needs, it must be regarded as *dependent* and is thus under extreme risk. This is debatable but obliges the definition of the surveyed region and its internal water sources at the very end. Table 2.4 illustrates the rating scale of the sub indicator.

Inter-Sectoral Competition

Competition is complex; when assessing competition, not only other competitors but also other resources must be regarded (Rhoades, 1995; Solow, 2008; Hunt, 2011). The resource in question is *available blue water*, which the energy sector needs to guarantee reliable generation.

In times of water scarcity, not only the water resource itself serves as a constraint for generation; other water-consuming sectors also serve as constraints, i.e., the domestic, agricultural, industrial and ecological sectors, according to Ziolkowska and Peterson (2016); Arthington et al. (2018).

Two conditions determine the limitations of such a competitively accessed, finite resource:

- The most massive threat that can provoke a consumption limitation is a tremendous resource scarcity in a certain time frame.
- Consumption inequality. the presence of a far stronger competitor/consumer poses a huge risk for smaller consumers. Volatile shifts in the demand patterns of the stronger competitor can easily consume a large fraction of the

resources needed by smaller competitors and can thus provoke resource limitations (Rhoades, 1995).

The herein introduced Inter-Sectoral Competition Indicator (ICI) is based on the Herfindahl-Hirschman-Index, which is used in economics to analyse the monopoly situation of a market (Rousseau, 2018). It is modified by a logistic function. Some further adjustments of a minor nature turn the Herfindahl-Hirschman-Index into a suitable indicator for measuring competition pressure in the face of water consumption inequality or harsh resource limitations. The ICI is bidirectional.

$$ICI = \begin{cases} \left(\left(\left(\frac{a}{a+b}\right)^2 + \left(\frac{b}{a+b}\right)^2\right)^{-1} + 1\right)^{\frac{1}{\frac{1}{2}+\frac{1}{4}e^{-4\frac{W-a-b}{W+a+b}}}} \text{for b > a} \\ -\left(\left(\left(\frac{a}{a+b}\right)^2 + \left(\frac{b}{a+b}\right)^2\right)^{-1} + 1\right)^{\frac{1}{\frac{1}{2}+\frac{1}{4}e^{-4\frac{W-a-b}{W+a+b}}}} \text{for b} \leq \text{a} \end{cases} \tag{2.2}$$

ICI = Inter-Sectoral Competition Indicator
a = Power Plant Water Consumption
b = Competitor (Industry, Agriculture, Domestic, Ecologic) Consumption
W = Unused Fraction of Available Blue Water

The subsequent results lead to a high penalty (power to zero) for water scarcity and a state of relief for water abundance (power higher than one). The formula results' risk classifications are displayed in Table 2.4.

2.6.2 Constraints due to Water

As soon as energy generation is dependent on water, it has to rely on the environmental water balance. This means that energy generation is subject to the qualitative and quantitative limitations of the hydrologic supply that occur within a certain region.

Engineers are expected to develop an energy generation system that is apt to cope with these limitations and withstand their variations to guarantee the sought-after energy outputs. However, the stricter the limitation and the more intense its variation, the less likely it is that water-dependent energy can continuously operate (Lohrmann et al., 2019; van Vliet et al., 2013).

In the recent past , climate change has proven to fortify the variations of, and thus heavily influence, these limitations (Lohrmann et al., 2019; van Vliet et al., 2013; McDonald et al., 2014; Flörke et al., 2018). This increases the risk that power plants will be forced to suspend generation due to insufficient water quantity or quality (Behrens et al., 2017) at a certain point in time, which undermines energy-water security.

Table 2.5: Constraints due to Water Sub-Indicators; WDL: Water Discharge Limitations, WTL: Water Temperature Limitations, DFV: Drought and Flood Vulnerability

Rating	WDL Rating	WTL Rating	DFV Rating
5	WDL > 10	WTL > 4.5	DFV > 4.5
4	10 > WDL > 5	4.5 > WTL > 3.5	4.5 > DFV > 3.5
3	5 > WDL > 3	3.5 > WTL > 2.5	3.5 > DFV > 2.5
2	3 > WDL > 2	2.5 > WTL > 1.5	2.5 > DFV > 1.5
1	WDL< 1	WTL < 1.5	DFV < 1.5

Water Discharge Limitation

Both hydropower and thermal energy are heavily reliant on a stable water supply. For reliable energy generation at an efficient rate, a rather constant water flux/level must be maintained.

There is, however, a growing number of cases in which unforeseen and prolonged dry periods lead to reduced power outputs or even shutdowns of entire plants (Hunt et al., 2018; Sanje, 2018). It is evident that proceeding climate change has led to high variations in the water level and temperature (van Vliet et al., 2013; Lohrmann et al., 2019; McDonald et al., 2014; Flörke et al., 2018); a fact, that was predicted by scientists (Förster and Lilliestam, 2009).

The identification of intensified variations in dry periods is thus a key point of risk indication that points out the risk for high temporal limitations of water quantity.

$$WDL = \log_{10} \frac{Q_{90}}{Q_{98}} * \frac{Q_{98}}{\Delta Q_{98}} + \log_{10} \frac{Q_{90}}{Q_{95}} * \frac{Q_{95}}{\Delta Q_{95}} \tag{2.3}$$

WDL = Water Discharge Limitations
Q_{90} **= Discharge surpassed by 90% within the pre-2000 period**
Q_{95} **= Discharge surpassed by 95% within the pre-2000 period**
Q_{98} **= Discharge surpassed by 98% within the pre-2000 period**
Δ **= Comparative post-2000 period**

The equation above emphasizes recent changes in critical low-flow events in comparison to general low-flow events. A rating scale is introduced in Table 2.5.

The base data are derived from local measurements. The suggested base period comprises the available data from 1971 (or 1981) to 2000. The suggested recent period is the post-2000 period.

This suggestion is based on restricted data availability (Behrens et al., 2017) and observed global temperature anomalies. From 2000 onward, temperatures have regularly surpassed the global long-term average by 0.5°C and greater (NASA, 2019). This warming process correlates with intensified riverine and precipitation variations that are palpable in many fluvial systems (van Vliet et al., 2013), even including the largest systems, such as the Amazonian basin (Marengo et al., 2018b).

Water Temperature Limitations

The higher the difference in a power plant's cooling water inflow temperature and internal steam temperature is after isentropic expansion in the turbine, the stronger the Rankine cycle's cooling effect is and the higher the power plant's efficiency is. In contrast, this means that higher riverine temperatures reduce power plant efficiency. In general, a drop of 0.4%/°C is notable (Durmayaz and Sogut, 2006; Ibrahim et al., 2014).

However, before a steam power plant's efficiency is substantially endangered (Kim and Jeong, 2013), critical ecological temperature limitations of the environment are surpassed. The heat output from cooling water increases riverine water temperatures locally and regionally (van Vliet et al., 2013; McDermott and Nilsen, 2014; Boogert and Dupont, 2005). Surpassing the ecologic limitations substantially threatens the local/regional flora and fauna (Hardenbicker et al., 2017).

Thus, some administrations oblige the operators of water-cooled power plants to comply with maximum water temperature values. In the case of a power plant exceeding those values, the operators have to reduce the production or even completely shut down the energy generation (Kovats et al., 2016).

Due to global differences in the long-term normal temperatures of riverine systems, such maximum values differ globally. For an indicator, a constant limitation value is thus not suitable.

Rather, an indicator must address a rivers'local long-term temperature variance. This follows a similar reasoning as that proposed in Chapter 2.6.2. Hence, the following equations are suggested:

$$WTL = \sqrt{\frac{PTE + LTC}{2}} \tag{2.4}$$

WTL = Water Temperature Limitations
PTE = Peak Temperature Events
LTC = Long-Term Temperature Change

One operator is the LTC, the long-term temperature change. It is based on the assumption that most aquatic ecosystems within a fluvial basin are able to withstand naturally occurring temperature deviations to a certain degree. As a naturally occurring tolerance level, the pre-2000 temperature that is surpassed in only 5% of all cases is chosen. Its difference from the pre-2000 mean temperature marks a bandwidth of naturally existing tolerance.

Due to climate change, the post-2000 mean temperature is supposed to surpass the pre-2000 mean temperature significantly. As this happened in, evolutionarily speaking, a rather short period of time, flora and fauna have not yet had sufficient time to cope with this new standard. The difference between the post-2000 and pre-2000 mean temperatures thus reduces the bandwidth of the naturally existing tolerance to extreme temperature events. This reduction is depicted by the LTC. A by 25% reduced bandwidth is seen as very critical.

The other operator is the PTE, the peak temperature events, which measures the intensification of extreme riverine temperatures. The more post-2000 peak events surpass the pre-2000 event average, the likelier it is that flora and fauna are damaged irreversibly. A 25% increase in peak temperature events is seen as very critical.

Equation 2.5 demonstrates the calculation of both the LTC and PTE. Their individual classifications are denoted in Tables S3 and S4 in the supplementary material. The result is used in equation 2.4 to obtain the final WTL indicator score, whose rating scale is illustrated in Table 2.5.

$$PTE = \frac{T_{ST5} - T_{LTM}}{T_{LT5} - T_{LTM}}, LTC = \frac{T_{STM} - T_{LTM}}{T_{LT5} - T_{LTM}} \tag{2.5}$$

$\boldsymbol{T_{STM}}$ **= Mean Temperature of post-2000 Reference Period**
$\boldsymbol{T_{LTM}}$ **= Mean Temperature of pre-2000 Reference Period**
$\boldsymbol{T_{ST5}}$ **= Temperature of post-2000 Reference Period surpassed by 5%**
$\boldsymbol{T_{LT5}}$ **= Temperature of pre-2000 Reference Period surpassed by 5%**

Drought and Flood Vulnerability

With the rising importance of renewable energy and the dependency of energy on biomass due to agriculture (Welfle, 2017; Thrän et al., 2010; Berndes et al., 2003), precipitation and irrigation(Crawford et al., 2012) via surface and subsurface water cannot be neglected.

Agriculture and biomass production are threatened by both extensive dryness and extreme floods. Both dryness and floods are currently subject to high and spontaneous deviations from the long-term equilibria (Cook et al., 2016; Leng and Hall, 2019). Therefore, a crucial linkage exists between energy security and the limitations given by surface and subsurface aquifer variations.

Several validated and highly renowned indication systems regarding droughts and floods exist. They differ, however, in their focuses, monitoring approaches and compositions. Thus, their ranges of validity are not completely congruent.

As the aim of this sub-indicator is the depiction of limitations due to subsurface, surface and precipitation variations, those indication systems need to be unified. The following well-proven indices and their adaptations are considered for this sub-indicator:

- *Standardized Precipitation-Evaporation Index (**SPEI**).* The system developed by Vicente-Serrano et al. (2010) is currently a widely recognized and recommended long-time drought monitoring tool (Tirivarombo et al., 2018). The intensity of a dry or wet event is categorized into classes ranging from -3 to 3.

  In concordance with the evident data from NASA (2019) the intensification of extreme events is indicated for the pre- and post-2000 periods. The focus is laid on the periods exceeding +/-1, and the evaluation is undertaken for all data points of a region. Their arithmetic average produces the resulting score, following the equation:

$$SPEI_I = \frac{t_{e1post}}{t_{post}} - \frac{t_{e1pre}}{t_{pre}} + (\frac{t_{e2post}}{t_{post}} - \frac{t_{e2pre}}{t_{pre}}) * 2$$
$$| \text{ if } t_{e1post} + t_{e2post} > 0.8 * t_{post} \text{ and } t_{e1pre} + t_{e2pre} > 0.8 * t_{pre} \quad (2.6)$$
$$\text{then } SPEI_I = 2$$

$SPEI_I$ = SPEI value
$t_{(...)pre}$ = pre-2000 time period
$t_{(...)post}$ = post-2000 time period
$t_{e(...)}$ = time period exceeding SPEI +/-1 or +/-2

The maximum value possible for $SPEI_I$ is 2. In areas that tend to be extreme for most of the time, the maximum value, and thus the highest penalization, is given automatically.

- *Gravity Recovery and Climate Experiment - Drought Severity Index (**GRACE-DSI**).* The remote sensing methodologies developed by Zhao et al. (2017) used NASA's GRACE satellite to detect patterns in changes in Earth's gravity and provide a viable methodology for evaluating severe droughts or wet events. These methodologies were evaluated and approved against SPEI values (Zhao et al., 2017).

  The categorization of the GRACE-DSI index ($GRACE_I$) works analogously to that of $SPEI_I$ (+/-1 moderate, +/-2 extreme). As the data series of GRACE-DSI is limited to post-2000 data, pre-2000 SPEI data is used for the pre-2000 values. The internal ranking is translated into a five-level categorization system, according to Table S6.

- *Groundwater Vulnerability Index (**GVI**).* The assessment of subsurface aquifers is a complex task with scarce data resources. This results in significant uncertainty or coarseness regarding the evaluation. Nevertheless, subsurface aquifer analysis is existent and usable, e.g., with the global GVI produced by the Federal Institute for Geosciences and Natural Resources of Germany (Federal Institute for Geosciences and Natural Resources Germany, 2015). The internal ranking is translated into a five-level categorization system, according to Table S7 with the GVI index (GVI_I).

The final drought and flood vulnerability indicator is composed as follows and is illustrated in Table 2.5:

$$IPV = \sqrt[3]{GDV_I * GRACE_I * SPEI_I} \quad (2.7)$$

DFV = Drought and Flood Vulnerability

2.6.3 Dependence on Water

The reliance on water as a main coolant makes regional energy generation extremely vulnerable to any event of hydrologic scarcity, especially if the event is prolonged. A prolonged drought would turn any water crisis directly into an energy crisis, which is highly undesirable (Hunt et al., 2018; Sanje, 2018). Following this view, reduced dependency is recommendable. However, the aversion of such a dependency by the usage of other technologies and/or another coolant currently comes with a significantly reduced efficiency (Bolognesi et al., 2014; Durmayaz and Sogut, 2006), which means economic loss and shifted impacts.

Table 2.6: Dependence on Water Sub-Indicators; CWD: Continuous Water Dependency, WRL: Water Replacement Losses, TC: Technological Capability

Rating	CWD Rating	WRL Rating	TC Rating
5	CWD > 95%	WRL > 8%	TC > 50
4	95% > CWD > 80%	WRL > 4%	50 > TC > 40
3	80% > CWD > 50%	WRL > 2%	40 > TC > 30
2	50% > CWD > 30%	WRL > 1%	30 > TC > 20
1	CWD < 30%	WRL < 1%	TC < 20

Continuously Water Dependent Energy

Hydropower and thermoelectric energy comprise the lion's share of global energy generation. Potentially, only 2.2% of currently produced electrical energy is independent of water (International Energy Agency, 2018). Among water-dependent regions, some countries are up to 80% dependence on surface water (hence excluding abundant sea water) (Yu et al., 2011). This also true for entire (electrical) island states (Byers et al., 2014).

To guarantee energy-water security, a diverse set of power or cooling sources is recommended to maintain both power output efficiency and high resilience in the case that water sources become scarce or unsuitable. Thus, the share of energy sources that are continuously (i.e., after being set into operation) dependent on surface water, groundwater or irrigation (hence excluding abundant sea water) shall be displayed as an indication. The scoring system (see Table 2.6) assumes that complete dependency is undesirable, while already small variance capacities are seen to be very beneficial due to enhanced resilience.

$$CWD = \frac{E_{WD}}{E_T} \tag{2.8}$$

CWD = Continuous Water Dependency
E_{WD} = Water Dependent Energy Generation of a Region per Annum

E_T = **Total Energy Generated in a Region per Annum**

Water Replacement Losses

Generally, water is the most commonly used coolant in the thermal generation of electrical energy due to its almost global accessibility, low cost and comparatively acceptable characteristics as a thermal conveyer (Winterbone and Turan, 2015). The only viable grand-scale alternative currently is air or dry cooling. However, these alternatives are accompanied by losses in output efficiency, especially for very high ambient temperatures (Sun et al., 2017; Qin et al., 2015; Wurtz and Nagel, 2010). With extremely high ambient air temperature, air cooling is known to cause up to 50% efficiency loss (Sun et al., 2017; Kutscher and Costenaro, 2002; Kanog˘lu and C¸engel, 1999). The relation is disproportionate.

The higher the efficiency loss is, the more investment, material imports and primary energy supply are needed to abate the assumed losses. Thus, water-dependency reduction comes with a price, which is depicted by this indicator as efficiency loss compared to conventional water cooling. The temperature thresholds orient themselves on prevalent marks to distinguish hot (or super hot) days in meteorological statistics. The penalty factors are roughly bounded to the numbers presented by Sun et al. (2017); Wurtz and Nagel (2010); Kutscher and Costenaro (2002); Kanog˘lu and C¸engel (1999).

$$WRL = \frac{E_{CW} - E_{ACS}}{E_{CW}} | E_{ACS} = E_{CW} * \sqrt[\sum_{i=1}^{4} D_i]{\prod_{i=1}^{4} P_i^{D_i}} \tag{2.9}$$

WRL = Water Replacement Losses
E_{CW} = **Energy Generated with Freshwater as Coolant in a region per Annum**
E_{ACS} = **Air Coolant Scenario for** E_{CW}
i = Rank, ranging from lowest to highest temperature phenomenon: 1: $T_(max)$**<25°C, 2: 25°C<** $T_(max) <$ **30°C, 3: 30°C<** $T_(max) <$ **35°C, 4:** $T_(max)$**>35°C**
D_i = **Days in a year of i occurrence**
P_i = **Penalty Factor for i: 1: 1, 2: 0.95 3: 0.9 , 4: 0.75**

The geometric mean is chosen for E_{ACS} to give the outstanding underperformance of air cooling on very hot days a higher significance.

The maximum WRL is 25%. The WRL indicates, how severe a region's loss of energy would be if the whole regional cooling was hypothetically converted to dry cooling. The whole rating can be consulted in Table 2.6.

Technological Capability

The ability of an area to apply and install measures to detach energy from water or to reduce the energy generation's overall water consumption to reduce risks and strengthen resilience is determined by the technological and scientific capabilities that exist in a given region or country. To develop or introduce new ideas and technologies, competent staff, institutes and companies must be available.

One of the few assessment tools that is regularly used to evaluate technological capability is the Global Innovation Index (GII), which works on a national scale (Wunsch-Vincent et al., 2018). However, it includes several governance and administrative indicators within its scoring system, which, in some experts' views, contort the validity of the indicator set regarding innovation (Skillicorn, 2016). Hence, if certain subcategories were spared (*institutions* and *market sophistication*), the GII can serve as an indication of a country's technological capability.

The classification of the Technological Capability (TC) scoring system used in this paper orients roughly on the GII's internal definition of *Innovation Leaders*, i.e., the leading countries in innovation. It can be consulted in Table 2.6).

2.6.4 Water Footprint

The life cycle of power plants and their respective main energy carriers must be regarded in light of the global origin of their components. The production of these components contributes to water consumption, not just locally but also in the regions of origin of the components. Therefore, power plants are similar to many other products subject to the water footprint (Hoekstra, 2017), and the same is true for the energy carrier used.

It is hence necessary to trace back the history of power plant formation and energy carrier extraction. Thus, the water footprint is mandatory to evaluate whether a given region causes energy-water connected risks in other areas on the globe.

For electricity generation, this means that water is not only consumed onsite, but is also consumed globally. The water footprint concept, which has been widely accepted and intensively refined in recent years by Hoekstra (2017), can be combined with the Life Cycle Assessment (LCA) to display direct and indirect global water use. The water footprint concept can be quite complex due to the highly diversified supply chains behind products and, in this case, power generation. The concepts proposed here thus seek to reduce the extent of the water footprints while ensuring methodological correctness.

Two main aspects of the water footprint will be assessed: 1. Water consumption, which refers to the difference between the water withdrawal and return flow and focuses on evaporative water losses, i.e., the evaporation volume (EV) (Hoekstra, 2017), and 2. Water quality, which is addressed by the virtual dilution volume (DV) and states the amount of water needed to dilute pollution.

The power plant life cycle was separated into two major operation phases: 1. The construction, material and maintenance of power plant, and 2. The extraction of the respective energy carrier needed to guarantee operation. This division helps to accentuate the influence on the water consumption of the respective energy source chosen.

Table 2.7: Water Footprint Sub-Indicators; PPMM: Power Plant Material and Maintenance, ECE: Energy Carrier Extraction

Rating	PPMM Rating	ECE Rating
5	PPMM > 7.5	ECE > 7.5
4	7.5 > PPMM > 2.5	7.5 > ECE
3	2.5 > PPMM > 1.5	2.5 > ECE
2	1.5 > PPMM > 1	1.5 > ECE
1	PPMM < 1	ECE < 1

Power Plant Material and Maintenance

This indicator accounts for an aggregated value of all electricity producers in the reference area that contribute more than 5% to the regional total electricity production. Production sites of similar types are pooled to facilitate this procedure.

To cover indirect impacts on water resources via the use of mineral commodities needed for the electricity generation of a plant, the origin of these commodities is considered. Therefore, four main commodities that sustain the greatest portion of the production site are selected: aluminium, copper, cement and steel.

Total evaporative water withdrawals (evaporation volume (EV)) for mining are calculated by comparing the withdrawals, in liter per ton of commodity, to the return flows, in liter per ton of commodity (determined in a previous step, following the method outlined in Schomberg (2020)).

The virtual dilution volume (DV) calculates the volume of water needed to dilute pollution below the thresholds of the WHO international drinking water standards (World Health Organization, 2018) according to the gray water footprint approach of Hoekstra et al. (2011). It is hence a measure for water quality.

The Available Water Remaining concept (AWARE), developed by a UNEP-SETAC working group (Boulay et al., 2018) is the current water stress consensus indicator for impact assessment in life cycle assessments (LCAs) according to Boulay and Pfister (2013) and serves as a good water footprint tool. The AWARE basin value displays the water stress of the respective basin. Water stress is expressed as the available water remaining after the demands of all human users and nature have been satisfied.

All three values are aggregated following Equation below while using the AWARE values of the respective region of origin of the commodity.

$$PPMM = \frac{\begin{array}{r} AW_o * (EV_o + DV_o) + AW_n^{n=1} * (EV_n^{n=1} + DV_n^{n=1}) \\ + ... + AW_n^{n=N} * (EV_n^{n=N} + DV_n^{n=N}) \end{array}}{EV_o + DV_o + EV_n^{n=1} + DV_n^{n=1} + ... + EV_n^{n=N} + DV_n^{n=N}} \quad (2.10)$$

$PPMM$ = Power Plant Material and Maintenance
AW = AWARE value

$$\boldsymbol{EV} = \textbf{Evaporation volume}$$
$$\boldsymbol{DV} = \textbf{Dilution volume}$$
$$_{\boldsymbol{o}} = \textbf{Region of power plant origin}$$
$$_{\boldsymbol{n}} = \boldsymbol{n^{th}} \textbf{ region of commodity origin}$$

The maximum value of AWARE is 100, expressing one hundred times less available water remaining per area than the global average (Boulay and Pfister, 2013; Boulay et al., 2018), with the global average being defined as 1. The further the PPMM value surpasses 1, the more devastating the water footprint of the respective power plant material is. The classification follows the system shown in Table 2.7.

Energy Carrier Extraction

This indicator accounts for an aggregated value for all electricity producers in the reference area that contribute more than 5% to the regional total electricity production.

A constant energy supply with energy carriers is the very heart of operation of a thermoelectric power plant. The exploitation of the carriers in question has considerable impacts on water consumption in the regions of origin. The water footprint of the energy carriers is thus displayed as a unique indicator.

Technically, the sub indicator *Energy Carrier Extraction (ECE)* is composed simultaneously to *Power Plant Material and Maintenance* (see Table 2.7). There are other central commodities that reflect the main energy carrier (such as coal, oil or uranium).

2.6.5 Feedback Effects

No other energy generation technology and hardly any other man-made construction sites are responsible for forming as tremendous alterations to nature as do hydropower plants (Gutierrez et al., 2019; Peñas and Barquín, 2019; Magilligan and Nislow, 2005). Despite the many economic and social benefits, reservoirs also possess the potential for negative aftermath in all four risk dimensions. If not managed carefully, hydropower structures can induce increasing pressure in basins (Snoussi et al., 2002; Aguiar et al., 2016).). In the long run, hydropower mismanagement can transform hydropower reservoirs into quite unsustainable structures (Sumi, 2015; Annandale, 2013). Thus, catchment alterations for the sake of hydropower are an important feature to investigate in regard to energy-water security.

Fragmentation Stress

The fragmentation of river basins by damming for hydropower or multipurpose dams intersects the habitat of organisms (Moilanen and Hanski, 2001). Ecologic life cycles are disrupted, sediment flows are altered or even stopped and thermal regimes disturbed when rivers are fragmented (Kedra and Wiejaczka, 2018), which endangers endemic fauna and flora(Grill et al., 2015). The ecologic water

Table 2.8: Feedback Effects Sub-Indicator; FS: Fragmentation Stress, SS: Siltation Stress

Rating	FS Rating	SS Rating
5	Combined *Severe*	SS > 70%
4	One-sided *Severe* and Combined *Heavy*	70% > SS > 40%
3	One-sided heavy	40% > SS > 15%
2	*Moderate*	15% > SS > -10%
1	*Weak*	SS < -10%

security is thus reduced. Additionally, the contribution of reservoirs to the warming of riverine systems causes adjacent water-cooled thermal power plants to lose efficiency, according to Kedra and Wiejaczka (2018); van Vliet et al. (2013); Lohrmann et al. (2019).

The effects gain power as an increasing number of dams are added in the same region. Under the current global trend regarding relaxed dam sustainability management (Annandale, 2013), the degree of fragmentation is hence regarded as an indication of rising long-term risk.

The dam impact matrix (DIM) from Grill et al. (2015), which itself is composed of the river fragmentation index (RFI) and the river regulation index (RRI), appears to be suited to meet this demand (Grill et al., 2015). It offers rather detailed insight into a respective region's fragmentation stress (FS). While the RFI is a measure of the integrity of a basin's stream flow, the RRI is a proxy for alteration induced by damming. Their unification makes the DMI a very useful indicator and its implementation to the indicator set is presented in Table 2.8.

Siltation Stress

Reservoirs have been installed as long-term assets to guarantee water and energy security for decades, if not centuries. However, the effect of siltation undermines reservoirs'sustainability because it significantly reduces the reservoirs'original capacity (Morris and Fan, 1998) and has impacts on downstream erosion and fertility (Schleiss et al., 2016; Snoussi et al., 2002).

Notwithstanding manifold siltation predictions and elaborate simulation models (Omer et al., 2015; Simoes and Yang, 2006; Zeleke et al., 2013; Ghimire and DeVantier, 2016; Hao et al., 2017), global development insinuates that planners, operators and practitioners struggle to predict both sediment inflow and yield reservoirs correctly. Consequently, the implementation of suitable management strategies to address siltation remains a challenge (de Vente et al., 2013; Yang, 2013; Schleiss et al., 2016; Kantoush and Sumi, 2017)that prevails regardless of the respective environment, climate, society and technology level, according to Annandale (2013); Basson (2009); Schleiss et al. (2010). It appears that planners, operators, managers and constructors are overly optimistic; i.e., they are biased by so-called optimism bias (Schleiss et al., 2016).

Recent research demonstrates how far sedimentation deviates from the originally aspired siltation goals (Landwehr et al., 2020). This difference was estimated using the siltation goal of the Japanese government (complete siltation after 100 years) using the the dead volume of reservoirs as comparative values.

For the indicator, the siltation of all reservoirs of a region is checked against this comparative value (complete dead volume siltation after 100 years). The average deviation from that norm expresses the underestimation of the siltation effect, which implies that the long-term security of the respective dams is not occurring as was originally planned. Thus, the degree of siltation, better siltation stress (SS), is used as the classification of risk. An underestimation of 70% is seen as critical, as can be seen in Table 2.8

2.6.6 Institutional Capacity

Administrative and jurisdictional restrictions often hinder a desirable implementation of beneficial energy and water policies that might help to reduce mutual risks via different means and incentives (technological, social, economic, etc.) (Locatelli et al., 2017; Pahl-Wostl, 2015). The institutional situation of a region is thus a crucial limitation on or facilitation of the establishment of energy-water security, depending on its respective capacity.

Table 2.9: Institutional Capacity Sub-Indicators; GL: Governance Level, CL: Corruption Level, EWL: Energy-Water Legislation, EWA: Energy-Water Administration

Rating	GL Rating	CL Rating	EWL Rating	EWA Rating
5	GL > 90	CL > 90	EWL > 4.5	EWA > 4.5
4	90 > GL > 64	90 > CL > 64	4.5 > EWL > 3.5	4.5 > EWA > 3.5
3	64 > GL > 36	64 > CL > 36	3.5 > EWL > 2.5	3.5 > EWA > 2.5
2	36 > GL > 10	36 > CL > 10	2.5 > EWL > 1.5	2.5 > EWA > 1.5
1	GL < 10	CL < 10	EWL < 1.5	EWA < 1.5

Governance Level

Kaufmann (2005) argued that the rise of the common good is the scale that indicates whether authorities within a country tend to comply efficiently with the reasons for which they were established. It can thus be inferred that bad governance is an inhibitor of efforts to increase the common good.

Energy-water security can be regarded as an increment of the common good, as it reduces risks towards fundamental human needs. This means that countries and regional governments have to create an administrative and legal environment to increase energy-water security. Therefore, the measurement and indication of the efficiency of governance are hence mandatory.

However, the elusive and unsteady character of governance poses a problem (Gisselquist, 2012). As it is not clearly defined, it cannot be clearly measured. Initiatives that attempted to quantify governmental structures and efficiencies ended up with highly variable results that defined governance in different manners, quantified it in different ways, measured it with different methods and included it into their internal scaling systems based on different principles.

It does not come as a surprise, then, that Arndt et al. (2006) came to the conclusion that a perfect indicator system for governance will probably never exist. An example is that is already appears difficult to compare two quite frequently used governance scoring systems, such as the Sustainable Governance Indicator (SGI) provided by Bertelsmann Stiftung (Schraad-Tischler and Seelkopf, 2018) and the Ibrahim Index of African Governance (IIAG) created by the Mo Ibrahim Foundation (Mo Ibrahim Foundation, 2018), which differ in data input, categories, target states and so on.

To obtain a rather concise overview, the NGO Forest Trends attempted an aggregation of some governance- or strongly governance-focused sets. The subsequent creation was called the National Governance Indicator (NGI). The NGI was developed due to the scarcity of specific data (in this case, contraband and forest protection) (Norman et al., 2017). As information about energy-water security governance suffers from the same problem, the holistic NGI method appears to also be suitable to support here expressing the governance level (GL) . The classification can be seen in 2.9.

Corruption Level

Many governance indicator sets define *good governance* in terms of Weber's ideal model of bureaucracy and evaluate their efficiency regarding this codex or in the spirit of a similar mind set. However, not all societies that perform acceptable or even supreme in guaranteeing energy-water security follow Weber' s model (Rothstein, 2015). Therefore, these countries tend to receive a rather unfavourable score by most indicators (Sen, 2011).

To remedy this situation, another governance aspect is needed: corruption as an indication of bad governance. Nearly all governance systems suffer from efficiency loss due to this phenomenon (Zhang, 2013; Locatelli et al., 2017). The higher the corruption score in a governance ranking is, the likelier it is that the water and energy authorities will not act in the spirit of the common good and will therefore tend to reduce water (Knieper and Pahl-Wostl, 2016) and energy security.

The aggregation of the corruption level (CL) indicator follows the NGI pattern (Norman et al., 2017)) and includes the following corruption measuring sets: the Corruption Perceptions Index, the Ethics and Corruption Sub-Index of the World Economic Forum's Global Competitiveness Report, the Control of Corruption portion of the World Governance Institute'and the Global Corruption Barometer, also provided by the NGO Transparency International. The classification scheme can be consulted in Table 2.9.

Energy-Water Legislation

The energy-water legislation (EWL) are the basis, on which sustainable and stable water distribution and energy generation systems must be built (Pahl-Wostl, 2015). However, the extent and variety of governmental structures in each country, region and department make it a challenge to judge whether the respective legislation indeed serves as the optimal base material for guaranteeing water and energy security (May and Daly, 2014; Ansaw, 2018).

Semi-guided (local or regional) expert interviews are seen as a good tool used to gain quantifiable insights into opaque and hard-to-judge structures (Adams, 2015). The interviews are oriented on a form provided in the supplementary material that also serves as an evaluation tool. The rating is presented in Table 2.9.

Energy-Water Administration

Administration is the executive action of a legal system and, by this definition, is a key component of governance (Pahl-Wostl, 2015). Any law in the respective code needs the human, monetary, structural and technical resources to be applied by monitoring, control and law enforcement (Halliday, 2013). Whenever there is a lack in said resources, the law will be made superficial or even worthless (Essien, 2015).

Another issue is structural variability: Within a country or a region the administration design can be highly diverse (Daniell and Kay, 2017). Country-wide evaluations can thus give only an impression that might be far from the respective true state in a particular region.

Administrative structures are hence quite challenging. Therefore, semi-structured interviews of local and regional experts serve as a viable tool for obtaining the sought-after insights (Adams, 2015) for energy-water administration (EWA). The interviews are oriented roughly on a form that is provided in the supplementary material and also serves as an evaluation tool. The rating is presented in Table 2.9.

2.6.7 Illustrative Example

After the aggregation process, the result for a fictive region just might look like Figure 2.6. The low values for *Water Footprint* tells us, that almost no water is consumed in outer-regional sources. Moreover, the *Institutional Capacity* appears to on rather satisfactory level with some opportunities for improvement. However, the *Constraints on Water* indicate that the region's water supply situation is rather unstable, whilst their is a high *Competition for Water* and high *Dependency on Water* for the electricity generation of the respective region. The Feedback Effects show that there are tremendous negative impacts on the riverine systems.

Such a situation might be comparable with the situation in the South Upper Egypt Region, which was introduced in Chapter 2.2.2. This is however just a

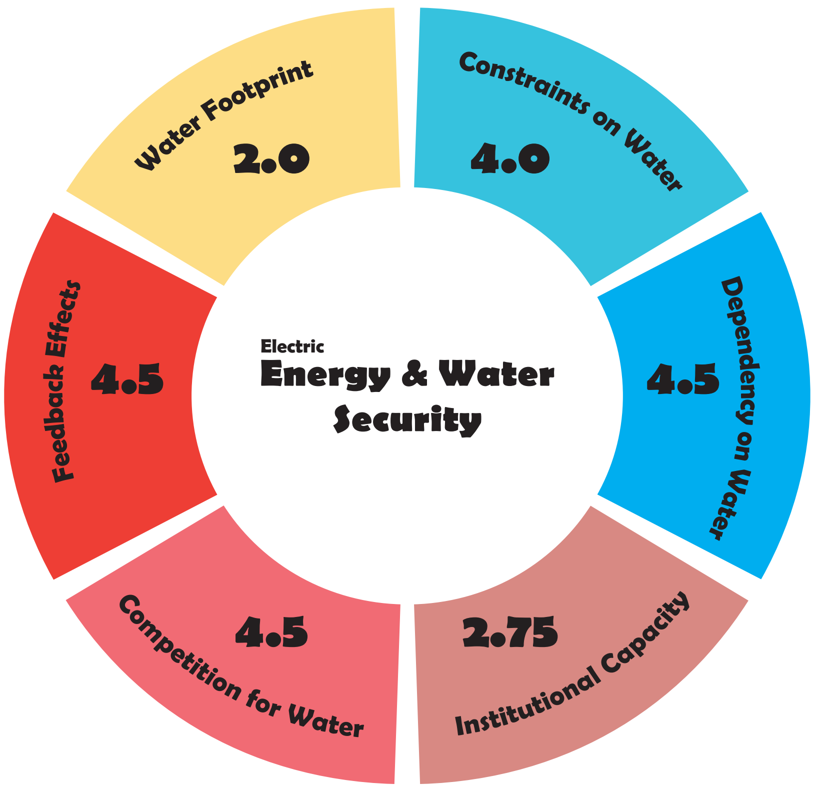

Figure 2.6: Fictive result with fictive numbers for the assessment system for a fictive region

very superficial comparison and in detail assessment via the indication system is needed and it is emphasized that the numbers of Figure 2.6 do not reflect a real survey in the South Upper Egypt Region.

An assessment with the indication would the interested user swiftly show, where the most urgent challenges for water dependent electric energy generation of that region are. Future and existent energy and governance infrastructure could thus be adapted in a secure, foresighted and sustainable manner.

2.7 Discussion

2.7.1 On the integration of the indicator set

There is no such thing as an ideal indicator set, not even for a single task or a problem, as Arndt et al. (2006) noted. This is because each to-be-indicated issue obliges the context-based subjectivity of indicator (extent) selection. This also holds true for energy-water security.

A good example is the W4EF, which already tackles the energy-water correlation and is completely functional in its physical data-driven mindset. The approach deals with the energy-water relation on a local scale (Lemoine and Bellet, 2015b). It thus complies with the view of power plant directors. Nevertheless, it is unsuitable for detecting structural problems.

In contrast, however, stands the SDG reductionist approach. The SDGs disentangle global challenges into different targets and operate from an overarching macroscale that strengthens problem realization. However, ostensible SDG separation might lead to a certain blindness or a simplification regarding interconnected issues (Zhang et al., 2016a).

The present paper jumps in as a gap closer that not only links SDGs 6 and 7 within the Brundtland perspective, but also chooses the yet untouched regional scale for the indication. It hence serves as a bridge between national/global goals and local hands-on problems.

2.7.2 On cross-SDG indicators

Is the approach of joining SDGs, such as SDG 6 and 7, under a common indicator view a new way to go?

From a very mathematical point of view, the answer must clearly be *no*. With 17 different SDGs, the mere number of combinations between any two SDGs would deliver 136 different indicator sets. Corresponding to a level-17 Pascal triangle, crossing two or more SDGs would create an abundance of 129,272 sets.

Thus, combining all possible SDGs is neither feasible nor desirable. Is the examination of more than one SDG at a time thus obsolete?

Again, by logic, the answer must *no*. The content of Zhang et al. (2016a); Pradhan et al. (2017) and the research herein clearly demonstrate the enforced interconnectedness between certain SDG subsets. Hence, the proposed energy-water security indicator must be seen in the spirit of selectively addressed cross-SDG issues.

2.7.3 On the definiteness of the indicators

The challenge of selecting the right method to create the necessary indicator is also present within this research. By no means are the obtained results meant to be exhaustive. The base data and research on which the indicators are found are the result of intensive investigation against the background of the aforementioned criteria. As those are, and will always be, subject to subjectivity and context, they remain (and shall remain) a matter to be argued.

In most cases, the methodology and data chosen were a compromise of such criteria. As a compromise is by definition an agreement with a non-optimal approach for each of the specific sides, but is an agreement that has the aim of a multilateral optimum (van den Hove, 2006); it will, and must always, allow room for new discussions and interpretations. By this approach, hopefully, the indicators will be a matter to be improved so that they will find their way into common practice.

2.8 Conclusion

This research offers a new, holistic approach, based on a profound set of main and sub-indicators, for enabling different stakeholders to judge the regional security of water-dependent energy generation. The indicator system is a toolbox that allows the user to evaluate their local energy security based on carefully reasoned out criteria and definitions that are flexible enough to adapt to the manifold different situations that arise in regional energy generation.

The set is, beginning now, open to the public and will hopefully find a use in common practice. This would push the set towards modifications and thus, hopefully, improvements due to scientific but also practical debates connected to the question of how to evaluate, monitor and implement the SDGs.

2.9 Acknowledgements

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2.10 Declaration of Originality

I declare that this research is my own work except where there is clear acknowledgement and reference to the work of others. This research does not contain material that has already been used to any substantial extent for comparable purposes.

CHAPTER

3

OVERCOMING PANACEA AND THE VERTO-HORIZONTAL DISCONNECT FOR THE WEF-NEXUS GOVERNANCE AT THE REGIONAL LEVEL – RESULTS FROM A PARTICIPATORY CASE STUDY ANALYSIS IN MOROCCO

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Abstract

The application and development of sustainable strategies apart from the prevailing panacea governance approaches is just rudimentarily realized or explored. This also includes the MENA region. The present paper identifies a - as we named it - verto-horizontal disconnect between stakeholders as one of the key reasons. Especially the disconnect between public professionals and other groups is a main obstacle, since public professionals on the local and regional level are the levers that realize strategy applications. Newly defined public action situation encounters are detected as a remedy and facilitator for sustainable non-panacea strategies. A public action situation encounter was realized by the third of a series of workshops in the Middle Drâa Valley, Morocco. It served to find the most attractive non-panacea solutions for the local WEF-Nexus challenges. According to a multi attribute decision methodology, stakeholders of the workshop found a)benchmarking, b)platform boards than include traditions and c)best practice guides to be the most promising solutions for their regional challenges. Via the workshop's realization, evaluation and analysis substantiations were obtained that indicate that the verto-horizontal disconnect can be overcome with public action situation encounters. By means of an emergence analysis, however, it became also apparent that trust in traditional top-down panacea solutions like national policy plans or grand multi-purpose infrastructures (e.g. reservoirs) is deeply enrooted within all participants. This rootedness needs to be harmonized with the opportunities that non-panacea approaches offer to reduce trade-offs between stakeholders and generate synergies suited to overcome WEF-Nexus challenges.

3.1 Introduction

Over two billion people are living in areas of high water stress and this number is rising (Programme, 2019). According to different climate scenarios half of the world's population will be facing stern water stress levels by 2030 (on Sustainable Water Management, 2015). The Middle East and North Africa (MENA) is one of he regions most affected by water stress, with all countries either already facing extremely high or high water stress levels today (World Resources Institute, 2019). Among these countries is also Morocco with its mostly semi-arid to arid climate and limited freshwater resources. The agricultural sector, which is the main consumer of water, accounting for more than 80% of the country's water consumption, is already affected by water scarcity, which is harming both rural livelihoods and the national economy as a whole (Verner et al., 2018). At the same time Morocco also faces severe challenges in the energy sector. Despite its ambitious renewable energy strategy, the country is still highly dependent on imports of fossil fuels (over 90%), which places an immense burden on both the national budget and the country's energy security (International Energy Agency, 2019). Furthermore, as result of the growing population, rapid urbanisation and economic development both energy and water demand are rising, while climate change puts additional pressure on the already scarce resources (Waha et al., 2017; African Development Bank, 2015). As a result, competition for water among local communities, municipalities, agriculture and industry activities is already evident and is expected to further increase in the future.

Against the backdrop of these multi-layer challenges an integrated approach is required to ensure the most sustainable pathways are chosen across the different sectors. The so-called water-energy-food nexus (WEF-nexus) approach (Hoff, 2011) is such an integrated concept that promises to help to reduce trade-offs and to build synergies across sectors thereby contributing to ensure a more sustainable development. Yet, while the concept has attracted wide recognition among international organizations, non-governmental actors and academia, its operationalization and application in practice is lacking behind (Leck et al., 2015). This is especially true for nexus analyses that go beyond quantification of material flows, technical solutions or resource efficiency aspects and address the social and institutional dimensions of nexus systems (Hoolohan et al., 2018). However, these types of analysis are particularly important because stakeholder constellations and institutions play a key role in decision-making processes and in the implementation within water, energy and food systems.

Accordingly, there has been a call by a number of scholars to put more focus on the governance aspects of the nexus (Weitz et al., 2017; Stein et al., 2014; Pahl-Wostl et al., 2010). WEF-nexus governance refers to the process of managing the institutional and actor-specific conditions in the political, social, economic and administrative systems that manage the supply and demand of water, energy and food (Pahl-Wostl, 2019, 2017). Whereby governance should not be understood as administrative-technical concept where better coordination and information between sectors lead to better system performance as measured against security or economy criteria (Weitz et al., 2017). Rather, governance should embrace the complexity of managing the decision-making processes and implementation within the WEF nexus, which includes, for example, negotiations between different actors with diverging interests and knowledge (Weitz et al., 2017).

In order to reflect the different perspectives and take into account the complex nature of the decision-making context, stakeholder participation is a central element (Bielicki et al., 2019). However, the participation of stakeholders in nexus analysis has so far been limited, with stakeholders often being mainly end-users of analysis results and not an integral part of the analysis process (Hoolohan et al., 2018). Yet, focusing on governance aspects of the nexus and involving stakeholders is especially critical in situations of increasing scarcity and potential conflict over resource use (Kurian et al., 2018) like in the case of scare water resources in the MENA region. Up to now, however, there have also been very few studies addressing nexus governance (Al-Masri et al., 2019) and applying the nexus concept in practice in the MENA region (Hoff et al., 2019).

In order to address these research gaps, this study examined governance aspects of the nexus together with stakeholders for a case study at local level in the MDV in southwestern Morocco. The MDV is severely affected by the declining water supplies, agriculture is the main source of livelihood, and the region is also home to one of the world's largest solar power plant complexes NOORo, which was recently completed. Of the three nexus components water supply and demand prove to be the most critical factors in the analyzed system. This is consistent with the research of Hoff et al. (2019), who showed in case studies throughout the MENA region that water scarcity is the dominant component of the nexus. Hence the main objective of this study is to identify suitable governance strategies for the implementation of water saving measures in the local context.

The analysis focus was deliberately put on the local level, because application of the nexus concept at the local level are widely missing. But it is precisely on the local level that people are directly affected by the nexus challenges (Terrapon-Pfaff et al., 2018; Stevens and Gallagher, 2015) and it is also at the local level where decisions are taken that largely determine whether and how efficiently strategies and measures within the WEF nexus context are implemented (Kurian et al., 2018).

In the light of the foregoing, the main research questions that are addressed in this paper are:

(a) What are preferred potential governance strategies to implement water saving measures in the local context in Morocco? (b) Are participatory and pragmatic governance strategies a requested or enrooted concept in a MENA based case study? (c) Do awareness, knowledge and acceptance of governance strategies vary between public professionals (PPs) and citizens? (d) Could the participatory approach contribute to establish a common ground among stakeholders in regard to the governance strategies to implement water saving measures?

3.2 Research Area/Case Study: Middle Drâa Valley

The governance aspects of the water-energy-agriculture nexus were analyzed for the case study of the Middle Drâa Valley (MDV), which is situated in southern Morocco spanning across the provinces Ouarzazate and Zagora. Ouarzazate and Zagora both belong to the administrative region of the Drâa-Tafilalet. The ephemeral Drâa river, which flows through the MDV is the longest river in Morocco. But with the catchment area of the Drâa river being one of the driest catchment areas worldwide the river falls dry after the town of Tagounit for most of the year.

To regulate the flow of the Drâa, the reservoir Mansour Eddahbi was constructed in 1972 close to Ouarzazate where the river begins (Heidecke et al., 2010). Rather than being discharged continuously, the water from the reservoir is supplied in larger quantities, known as lâchers about seven times a year, with varying quantities to supply also the southern oases with water (Heidecke et al., 2010). Main contributors ate the rivers Dades and Asif n'Tidili/Asif Iriri. Their locations are displayed on the map of Figure 3.1. The majority of the water is used for agricultural irrigation the riverine oases.

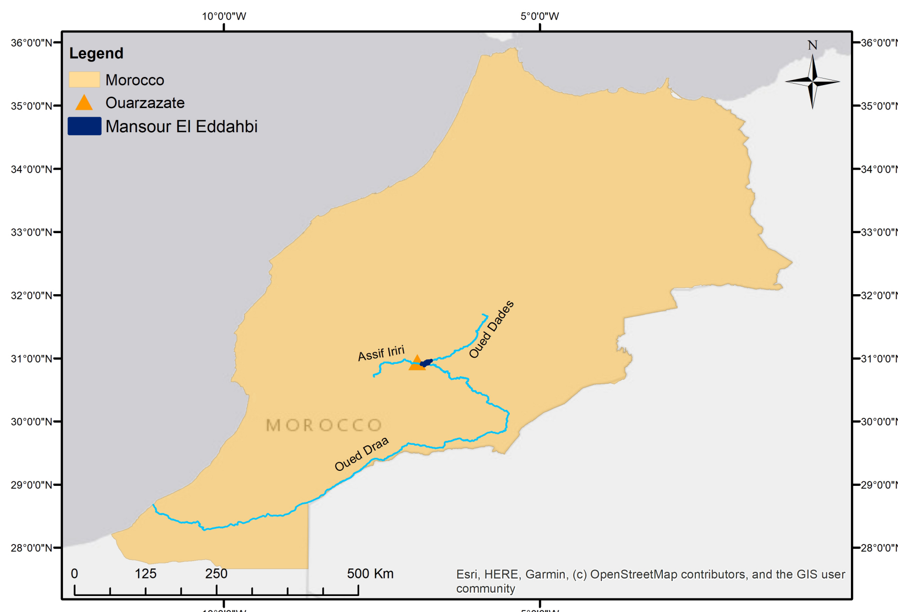

Figure 3.1: Ouarazazate, the Mansour El Eddahbi, the ephemeral Wadi Drâa and its main contributors in the MDV

Small-scale farming and subsistence agriculture are the most widespread form of agriculture and the main source of livelihood in the MDV. However, with the region already suffering from declining precipitation, increasing temperatures and severe droughts the water supply is declining putting local livelihoods at risk (Schinke et al., 2015). At the same time the water demand in the agricultural sector is increasing due to the rising cultivation of cash crops such as watermelons. But also, the water demand in other sectors is expected to increase due to changing lifestyles and growing urbanization but also due to new uses such as energy production.

The arid environment and the high solar radiation provide ideal conditions for solar energy and one of the worldwide largest solar complexes with a total capacity of around 580 MWp. was completed in Ouarzazate in 2019. The newly built solar power complex NOORo also sources its water from the El Mansour Eddahbi reservoir. Yet so far, the power plant accounts for only less than 1% of the local water demand compared to 96% of water used for agriculture purposes (own calculations based on Heidecke et al. (2010); Busche (2013); Karmaoui et al. (2016); Schinke et al. (2015).

Yet with the diminishing water supply also the water use for energy could become more critical, while the power plant itself could be negatively affected by water shortages in drought years (Ersoy et al. 2020). Based on the current distribution and the results of stakeholder preferential ranking of water saving measures (Terrapon-Pfaff et al. 2021), it seems to be the most reasonable approach to reduce water consumption in the agricultural sector and at the same time make local livelihoods more resilient to water scarcity.

How suitable governance strategies for the implementation of such water saving measures could look like in the local context will be discussed in this paper.

3.3 Theoretic foundation: WEF Strategies and the obstacles of verto-horizontal disconnect

3.3.1 About prevailing panacea strategy approaches

Following Hoolohan et al. (2018); Hoff et al. (2019); Al-Masri et al. (2019) and Pahl-Wostl (2019); Ostrom and Cox (2010) the majority of the contemporary WEF-Nexus concepts are of technical or theoretic panacea nature. Ostrom and Cox (2010); Ostrom (2007) utilizes *panacea* as problem definition for overly simplistic political analysis and approaches that shall remedy challenges with highly diverse backgrounds. Indeed, (qualitative) governance approaches appear to be scarce in the WEF context (Albrecht et al., 2018).

However, as Pahl-Wostl (2019) and Young (2013) point out, human- environment interactions (and thus WEF interactions) succumb to a manifold of known and unknown drivers. The unknown factors introduce a fraction of chaotic complexity that can hardly be deciphered in its entirety (Orsini et al., 2019). Young (2013) postulates that human-environmental systems underlie *complex causalities*. WEF interactions hence elude panacea approaches.

Decisions on applied strategies to remedy multilevel WEF challenges are frequently met in complex local environments of highly diverse character (Pahl-Wostl, 2019; Hagemann and Kirschke, 2017). Affected and active stakeholders are therefore to a significant part local. On the contrary, the predominant panacea approaches act delocalized and convert stakeholders more than often into simplified placeholders or passive end-users (Hoolohan et al., 2018). Panacea approaches are thus unsuited to meet local challenges as described in the MDV.

Contemporary administrations and governing bodies begin to reflect that panaceas will not suffice to meet the WEF challenges. A slow trend towards citizen empowerment (strategies)(Späth and Scolobig, 2017) is palpable (Igalla et al., 2019). Frequently, though, this trend does just reach certain, already politicized classes (Gourgues and Sainty, 2011) or it is not yet part of the governing bodies' strategy (Hvidman, 2018; Irvin and Stansbury, 2004) as shown e.g. by the Plan Maroc Vert (Green Morocco Plan, PMV), where - despite its good fundamental approaches - a lack of participation is noted (Faysse, 2015; Faysse et al., 2018; Bouzidi et al., 2020).

The level of participation and empowerment policies varies extremely from country to country and region to region. Systems that favor accountability and decentralization tend to implement the active local level integration and citizen empowerment. Administrations with a higher demand for control and centralization are more prone to reject them (Pacione, 2019).

3.3.2 The verto-horizontal disconnect between public professionals and citizen stakeholders

A decisive key role in the implementation of new (and non-panacea) policies is to be attributed to the public professionals (PPs) at the local *front-end* of administration. Their unwillingness can spoil strategy applications entirely (Tummers et al., 2009; Tummers, 2011). This is one of the reasons, why seemingly promising decisions taken at the national or regional level frequently have none or even opposing effects at the local level (Pacione, 2019). Local PPs and their attitude towards non-panacea strategies that empower and include local stakeholders are thus the focus of the present research. It is postulated that the local PPs' contemporary relation to citizens and local stakeholders is affected by a systematic alienation that needs to be overcome.

PPs - the agents of public administrations - are according to Jacob (1969) and Stillman II (2017) characterized by *applied expertise, corporate identity, and ethical responsibility*. Those three traits are central reasons of the alienation.

Though the first characteristic supplies PPs according to Stillman II (2017) with a *a higher status*, it *is negatively correlated with compassion, defined as being emotionally (empathically) based motivation to do good for others by improving public service delivery* as Andersen and Pedersen (2012) describes it. Additionally, Stillman II (2017); Gibb (1966); Noordegraaf (2011) detect further alienating effects in the second characteristic: Corporate identities (enforced by educational practices, codes of conduct or methods of enforcement) create hidden hierarchies, that vertically disconnect PPs from citizens and horizontally (via competition) from other administration entities. Lastly, the third characteristic entails PPs on a higher moral standard: The PPs represent - in theory - the cutting edge of a selfless morality bound for the public good. PPs are measured by this standard and therefore subject to higher pitfalls. (Perceived) Infringements by PPs (i.e. perceived corruption) can thus lead to extreme forfeiture of trust (Svara, 2014). All three PP characteristics are thus reasons for citizens to not reach the PP. They therefore cause a vertical bottom-up disconnection of citizen and local stakeholder distrust.

This vertical disconnection is complemented by top-down elements described by Bartels (2013); Hvidman (2018); Hoppe (2011). Governance modes of hierarchic or similarly enclosed character separate PPs from the citizens as part of their inherent system structure. The governance modes create (feedback) information gaps, i.e. PPs are unaware of the actual effects that executed or planned policies have among citizens and local stakeholders Bartels (2013); Fung and Wright (2001). This is especially valid in climate change (and WEF) contexts (Bednar et al., 2019; Bednar and Henstra, 2018) as demonstrated for the MDV by research regarding the Green Morocco Plan Faysse (2015); Faysse et al. (2018). PPs are hence vertically top-down disconnected through a separated professional and citizen reality Lipsky (1980). Citizens governed by such governance modes tend to judge public administration and public professionals as ineffective, unspecific and wasteful (Hvidman, 2018).

The disconnect is, however, not just of two-way vertical, but also of horizontal character as implied by Stillman II (2017); Gibb (1966); Noordegraaf (2011). Next to their indications, insufficient systemic persistence to carry out a horizontal policy integration and a missing focus on stakeholder interconnection in policy application are key features of the horizontal disconnect (Raymond et al., 2010). The horizontal dimension is especially evident in natural resources management (and thus WEF) contexts (Potts, 2019; Schafer, 2016). It is not only restricted to the administration level but also includes horizontal disconnects in the citizen stakeholder level as it was emphasized by e.g. Bouzidi et al. (2020).

The verto-horizontal disconnection (for the purpose of phonetic convenience not *vertical-horizontal*) depicts a communication gap between citizens and public professionals (Bartels, 2013) displayed as a sketch in Figure 3.2. Often, this gap is maintained by internalized communication and a multi-level speaking style (Howarth and Griggs, 2006).

In the context of the WEF-Nexus (Halbe et al., 2015) and the modern striving for sustainability (United Nations, 2015; Bednar et al., 2019; Bednar and Henstra, 2018) interaction between citizens and PPs is, however, mandatory (Halbe et al., 2015). Considering the key role of PPs in policy implementation the overcoming of the verto-horizontal PP-citizen communication gap is essential for the successful application of non panacea strategies in the sustainability spirit of the Brundtland commission (World Commission on Environment and Development, 1987). Hence, approaches are needed to downsize the disconnect and create a common ground of understanding between PPs and citizens that

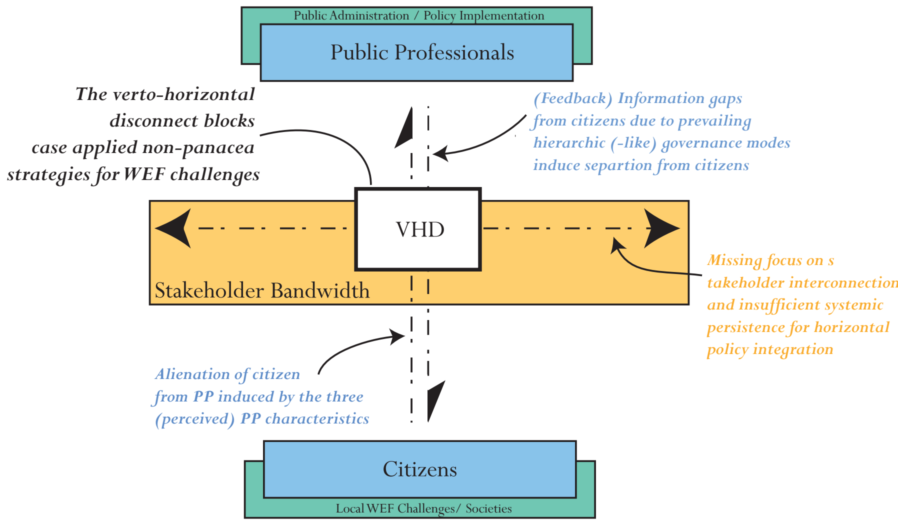

Figure 3.2: The verto-horizontal disconnect as strategy inhibitor

eventually leads to harmonized, sustainable action, adapted to the local level.

3.3.3 Public action situation encounters as facilitator for non-panacea strategy implementation

As locality contrasts the complex over-regional singularity of panacea (Young, 2013; Orsini et al., 2019), promising means to downsize the disconnect are found on the local level, where they are part of a diagnostic pragmatism and pluralism (Godfrey and Lewis, 2018; Pahl-Wostl, 2019). Action situations and public encounters (Pahl-Wostl et al., 2020; Knieper and Pahl-Wostl, 2016; Bartels, 2013) are two of such locally acting means. Literature identified them as methodologies suited to prepare ground for the sustainable implementation of non-panacea WEF challenge strategies (Knieper et al., 2010; Bartels, 2013). A combination of both thus seems desirable.

Action situations are characterized by their purpose (e.g. amending of climate change challenges, design of sustainable strategies in WEF context), level (e.g. local, regional), phase (e.g. implementation, design) and primary context (e.g. farming, electrical energy administration, flood amending) in which they are embedded and which usually last several years. Action situations are designed in semi-structured multistep processes, i.e. process designs of encounters, each of which producing specific outcomes that are (partly) replicated in subsequent action situations (Knieper et al., 2010; Pahl-Wostl et al., 2020). An actions situation itself is characterized by a structuralized social interaction, preferably in an analog-physical design, though digital-distance alternatives are finding increasing popularity nowadays.

Actors that participate pursue in general the overall action situation purpose, however in their own interpretations (Knieper et al., 2010). Those interpretations diverge from the ones of other actors or even contradict them. The divergences are in part motivated by the strategic necessities of the actors, but in part rooted in the verto-horizontal disconnect that creates separated thinking spheres. The participatory and pragmatic character of action situations that designed for interchange of opinion (Knieper et al., 2010) makes them suited to reduce the disconnect between actors, especially in the form of a public encounter.

Public encounters are the very essence of PP-citizen interaction as they reflect the *in-between* (Bartels, 2013) of that relation. They are a means of *doing and being together* (Catlaw and Rawlings, 2011). Public encounters involve measures of relation building *through which people learn to communicate with others with very different backgrounds, ways of thinking and ways of valuing* (Bartels, 2013). Those relations include family like elements like dependencies and role differences.

The theorem of this research is thus that in a series of *public action situation encounters* PPs and citizens constructively learn to settle those differences in order to avoid *the infliction of the real damage*, as Bartels (2013) describes it. Due to the flexibility of the action situation this process is inherently pragmatic and due to the character of the public encounter also inherently participatory in the sense of Godfrey and Lewis (2018). The latter's *in-between* character is optimally suited to downsize the verto-horizontal communication gap, and assist in implementing local non-panacea strategies to overcome WEF challenges. Failing the WEF-challenges would be equal to the aforementioned *infliction of the real damage* of Bartels (2013).

3.3.4 State of pragmatism and participation within the Green Morocco Plan

In recent times, participatory and pragmatic approaches gained more and more weight in developed democracies. Nevertheless, a new balance with the conventionally existing top-down administrative processing is not yet found (Falanga, 2019; Hoppe, 2011). A manifold of applicable strategies for WEF issues already exists (Hagemann and Kirschke, 2017), also in emerging and developing countries (Zaidan et al., 2019; Lumosi et al., 2019; Faysse, 2015). However, pragmatic and participatory governance approaches are still in an exploratory phase (Fayiah et al., 2020; Terrapon-Pfaff et al., 2018; Faysse et al., 2018).

This includes also the MENA region, in which the MDV is located. Cases that try to downsize the verto-horizontal communication gap to establish non-panacea strategies in the WEF context are restricted to a limited number of examples (Zaidan et al., 2019; Al-Masri et al., 2019; Hoff et al., 2019; Terrapon-Pfaff et al., 2018). This correlates with the fact that MENA region states traditionally tend to be be more on the *control and centralization* site of governance (Marshall and Cole, 2017; Mo Ibrahim Foundation, 2019), where the introduction of such measures is more unlikely (Pacione, 2019).

The example of the Green Morocco Plan policies and strategies draw clearly the picture of the verto-horizontal disconnect that includes the MENA region. It is the most ambitious and one of the best financed policies within the Moroccan Department of Agriculture and Marine Fisherey (DoA), comprising several hundred agriculture projects considerable influence for the case study area and the WEF governance within Morocco.

The Green Morocco Plan encompasses policies, strategies and a rationale that as such are suited to deal with WEF challenges. However, as Faysse (2015) stresses, the Green Morocco Plan a) does *not take the diversity of farms into account*, b) treats local citizen stakeholders as rather theoretical concept and c) only consulted affected stakeholders (farmers e.g.) in a *marginal* fashion. The Green Morocco Plan is hence part of the panacea approaches described by Pahl-Wostl (2019) via a top-down disconnect Faysse (2015) that also nourishes bottom-up reservations Faysse et al. (2018); Faysse (2015) and horizontal ambiguities Bouzidi et al. (2020). Faysse (2015) urges thus for practical and pragmatic inclusion of local citizen stakeholders in the development of applied strategies. The aforementioned *public action situation encounter* theorem conforms to the appeal of Faysse (2015) for the MDV.

3.4 Methodology

The methodology part encompasses the setup of workshops as public action situation encounters and the treatment and evaluation of the gained data.

3.4.1 Workshops as public action situation encounter

The theorem was carried out in the form of three interlinked one-day multi-stakeholder workshops, each of them representing a *public action situation encounter*.

The attendee size of said workshops was kept moderate with n $\approx$ 25, which corresponds with group sizes that guarantee interaction and participation (Allen et al., 2020).

The attendees were part of different sectors and participated as representatives of the respective sectors. For the sake of the research, they were categorized into the two prevailingly investigated groups in this paper: Public Professionals (Administration) and Citizens (Civil society, Agriculture, Science).

Each of the workshops set a different focus: Workshop I centered around scenario building for the MDV, workshop II around suited measures to be taken to deal with the WEF challenges, workshop III focused on governance strategies to implement the favored measures.

The specific outcomes were (partly) decisive for the respective subsequent workshop. Each of the workshops was set up in a participatory, non-hierarchic and collaborative way. The specific workshop III results are presented in this research. The whole process is displayed in Figure 3.3.

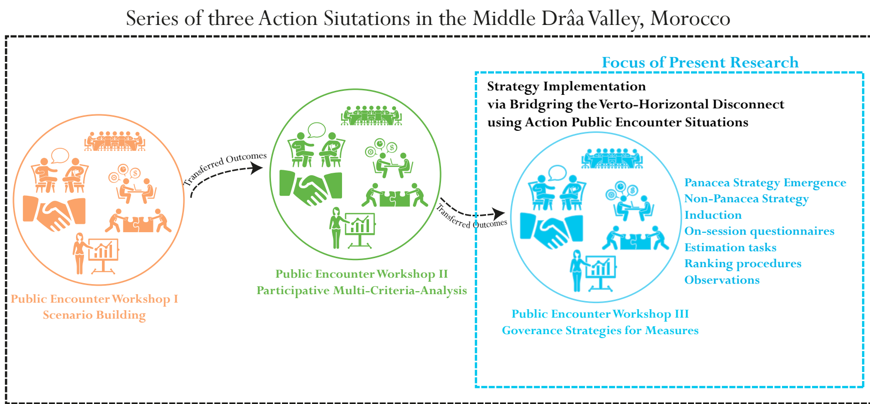

Figure 3.3: The public action situation encounter process in the MDV

During the workshops, interactivity played a key role to avoid passive group dynamics, especially in workshop III. Activity techniques like break-out and grand discussions as well as informal exchange and question sessions were utilized to create active, solution focused dynamics to break social group borders and create real public encounters (Lei and Lehmann-Willenbrock, 2015; Lehmann-Willenbrock et al., 2017; Endrejat et al., 2020).

3.4.2 Pragmatic and participatory strategies and emergence

Workshop III set a focus on the debate on which governance strategies were seen as useful by the stakeholders. This should foster the implementation of four selected water saving measures in order to increase the local resilience and reduce competition over the scarce water resources. The water saving measures for which the governance strategies were discussed represent the four preferred measures identified in the multi-criteria assessment conducted in workshop II. They are

- Irrigation activities: M1
- Efficiency of irrigation systems: M2
- Efficiency of water distribution: M3
- Crop choices: M4

Governance strategies can be subdivided into two classes: a) Pragmatic, participatory strategies and b) top-down (panacea like) attempts.

At the workshop, a set of of seven selected strategies from category *a) Pragmatic, participatory strategies* (see table 3.1) was introduced (not counting strategy 8 (S8), that was treated separately (see Chapter 3.5.6)), debated and evaluated with the participants.

The strategies were pre-selected based on already existing applications (table 3.1) and their potentially pragmatic and participatory character. In doing so the workshop followed Hagemann and Kirschke (2017)'s call to implement and adapt already known WEF challenge strategies, in order to fortify and deepen systemic interdisciplinary governance research.

Table 3.1: The seven introduced pragmatic and participatory strategies with use case examples South African Sugarcane Research Institut (2019); Region Bayreuth (2019); Breulmann (2018); O'Keeffe (2011); Förster (2005); Connor et al. (2016); Coté (2016); Gawel and Bretschneider (2012); Neumueller (2000)

	Strategy	Brief Description	Applied Use Case	Source/Reporting
S1	Best Practice Guides	Best practice guides summarize the possible and optimal range of activities under a given legal set.	South Africa	South African Sugarcane Institute (2019)
S2	Benchmarking	Benchmarking entails a comparative analysis of the performance based on pre-defined indicators	South Africa	South African Sugarcane Institute (2019)
S3	Intermunicipal Contracting	A flexible intermunicipal contract is a written voluntary-based co-operation agreement	Upper Franconia; Germany	Region Bayreuth (2019)
S4	Intermunicipal Cooperation	The formation of a body for intermunicipal cooperation is generally a response to capacity / resources bottlenecks.	Valle del Nalon, Spain	O'Keeffe (2011)
S5	Interdepartmental Offices	An office or council under the auspices of one ministry or department, which brings together representatives from different ministries/departments	Jordan	Breulmann (2018)
S6	Organization Culture Transformation	Interventions of organization culture change entail a management restructuring, explicit values, and new roles and practices.	Queensland, Australia	Förster (2005); Conner et al. (2016)
S7	Platform Creation with Explicit Inclusion of Traditional Methods/Leaders	A coordinating platform forms a multistakeholder board that addresses the implementation and discussion of regional issues like of e.g. a river basin plan or a lake protection plan, in this case with explicit implementation of traditional methods/leaders.	Minnesota, USA; Ontario, Canada	Coté (2016)
S8	Water Withdrawal Charges	System that charges withdrawal of water from a region's/country's water resources.	Federal States; Germany	Grawel (2012); Neumüller (2000)

On the other hand, top-down(-like) policies and strategies like those of the Green Morocco Plan were not introduced. However, participants were given in several occasions the active chance to freely mention, discuss and attribute strategies (and top-down plans) that appealed to them.

This approach was utilized to check the *emergence* of top-down (panacea) approaches at the local level and within (PP or citizen) stakeholder groups.

Emergence is understood as process that arises naturally or self-organized and are thus opposed by deliberative or designed processes (Lumosi et al., 2019;

Cundill and Rodela, 2012). *Emergent* processes are thus significantly deeper rooted in the stakeholder than deliberate setups. Therefore, they are highly considerable motives for acting and decision making.

3.4.3 Data collection pattern

On-session questionnaires, estimation tasks, ranking procedures and observations were utilized to gather data for seven different stages, which are:

1. Pre-Workshop Strategy perception
2. Emergence of Strategies
3. Strategy ranking during workshop activities
4. Strategy evaluation after workshop activities
5. Post-Workshop rapprochement of stakeholder parties
6. Strategy 8: Effect of equi-distribution of information
7. Future objectives

The results for each stage are processed and reflected in Chapter 3.5.

3.4.4 Evaluation of data

To answer the research questions from chapter 3.1, the data was evaluated regarding a) the attitude towards the seven introduced strategies, a) emergence and c) evidence that the verto-horizontal disconnect was downsized. The evaluations is presented and discussed in Chapter 3.6

Strategy Preference

The preference of strategies succumbs to various points of view. What appears to be preferable for some sectors might not preferable to reach certain goals like the measures mentioned in Chapter 3.4.2. Furthermore, stakeholders might tend to act and rank strategies differently in an open discussion compared to a non-open classification and ranking, e.g. in a questionnaire.

To correspond to both the point of view question and the open/non-open ranking conditions, a mixture of three ranking conditions was chosen and utilized for a final ranking: a) A strategy ranking derived from a mixed-stakeholder break-out group task for the mentioned measures of Chapter 3.4.2; b) a Simple Additive Weighting (SAW) as part of Multi Attribute Decision Making (MADM) (Poorzahedy and Rezaei, 2013; Koksalan et al., 2013) for mentioned measures (SAW-measure) c) a Simple Additive Weighting (SAW) for mentioned sectors (SAW-sector).

The break-out-group-ranking (BOG) is created in the course of stage 3 from Chapter 3.4.3.

The corresponding data of stage 4 from Chapter 3.4.3 from Figure S6 and S5 from the supplementary were used to generate normalized decision matrices for both the measure-SAW and the sector-SAW.

Preference rankings from the workshop II were used to determine the decision makers' weight matrix for the measure-SAW. Likewise, results from Chapter 3.4.3's were utilized to generate the decision makers' weight matrix for the sector-SAW. The workshops' participants, i.e. the stakeholders in the MDV, were According to the MADM (Poorzahedy and Rezaei, 2013; Koksalan et al., 2013) in both cases defined as decision makers. This corresponds with the participatory and pragmatic approach of the present paper.

The three rankings were summed and an overall ranking generated, using a higher absolute pre-ranking position as tie-breaker.

3.4.5 Emergence

In two occasions, participants were given the opportunity to bring forward *emergent* ideas, namely in stage one and two of Chapter 3.4.3.

The gained data was evaluated regarding its panacea or participatory and pragmatic nature, respectively; a literature review of the the core of the analysis. A detailed, in-depth analysis like the one executed by Faysse (2015) for the Green Maroc Plan for each mentioned policy/organisation/program (p/o/p) to define its prevailing character was, however, out of bound for the research. Instead, literature research for every p/o/p with more than two mentions in stage one of Chapter 3.4.3 was utilized as a non-exhaustive proxy to classify the respective program's state of pragmatism and participation.

3.4.6 Downsizing of the verto-horizontal disconnect

Discordance metrics were necessary to measure, whether a downsizing effect of the pragmatic and participatory workshop activities verto-horizontal disconnect was measurable. Pre- and post-activity data was thus surveyed.

The share of of positive PP or citizen statements, respectively, from Chapter 3.4.3, stage one, were used to generate numbers for the pre-activity-discordance. The underlying data generated from Chapter 3.4.3, stage five and six, was used for the post-activity-discordance.

Due to the workshop participant number root-mean-square was used for this task instead of usual metrics like the one of Spearman or Pearson (Hauke and Kossowski, 2011).

$$D = \sqrt{(\frac{1}{n})\sum_{i=1}^{n}(y_i - x_i)^2} \tag{3.1}$$

D=Degree of Discordance n = number of questions utilized
y = Fraction of positive PP answer
x = Fraction of positive citizen answer

The formula measures the root-mean-square of the discordance between the citizens and PPs. The root-mean-square was chosen as it neutralizes the problem of distortion caused by negative or positive distances. Lower post- to pre-activity numbers are seen as indication for lowered discordance between stakeholder, i.e. a higher concordance among them and thus a reduced verto-horizontal gap.

Moreover, a qualitative test was carried out via 3.4.3, stage 7. It was tested, whether a detailed presentation of concept and application of and a brief debate on strategy 8 - a highly controversial strategy - would lead to shifted views, i.e. whether an equi-distribution of information would lead an assimilation in citizen and PP opinion in respect to such a controversial strategy.

3.5 Results

Due to the workshop setup The results have indicative character. Nevertheless, this is still very significant, as other sources on the specific matter are scarce (Zaidan et al., 2019; Al-Masri et al., 2019; Hoff et al., 2019; Terrapon-Pfaff et al., 2018) It is precisely for this reason that the results of this study of limited participant size provide valuable insights and evidence within the current transformative process of MENA WEF governance.

3.5.1 Strategy perception and (top-down) policy emergence

In a first step, participants evaluated strategies of table 3.1: The evaluation included: a) Knowledge about the strategy b) Confidence in the strategy c) The assumption, whether the strategy is already applied in the MDV d) The presumption, whether the strategy would have had any positive effect regarding the WEF challenge in case that c) was affirmative (s. tables S1 to S4). The answers were subject to high diversity.

The divergence between the PPs (Administration) and citizens (Civil, Agriculture, Research) is of special interest. Whilst the PPs are almost consistently affirmative about knowing mentioned strategies, the knowledge about them among citizens is stated to be limited. The same holds true for the confidence in the strategies and their estimated applicability. Most interestingly, the opinion that applied strategies are already exercising a positive effect within the WEF challenge is almost exclusive to the PP group (though the PP group's estimate is not consistently uniform for each strategy).

Among the strategies, *S1 - Best Practice Guides* takes on a special position. Though they seem to be little known, the confidence in them is comparatively high. In fact, it appears to be the least known strategy, following *S6 - Culture Transformation*. *S2 - Benchmarking*, S3 - Intermunicipal Contracting and *S7 - Platform with Tradition Inclusion* are the most widely known strategies with a near to complete coverage.

As mentioned above, alongside with S7, S1 receives the highest confidence regarding its capability to overcome the WEF challenges in the Drâa valley.

Interestingly, the widely known S3 obtains with distinction the lowest confidence and is rather mistrusted. This is due to the high number of citizens that object that S3 would be a suitable method.

Regarding the question whether the strategies are already applied, S1 and S6 receive the lowest affirmation. S6 is, moreover, the only strategy, where more PPs negated than affirmed an assumed application. S2 and S3 reach the highest values of perceived application.

A high fraction of participants refrained from judging, whether the perceived application was efficient or not regarding their capability to overcome the WEF challenges. The answering fraction mainly consisted of affirming PPs, with S3 receiving the highest degree of affirmation and S6 the lowest.

Each participant had the opportunity to name a p/o/p that applied the respective strategy in the MDV to their knowledge. The number of mentions was not limited, no policies, organisations or programs were previously mentioned or specified. As such, the referred strategies of Figure 3.4 are exclusively *emergent*.

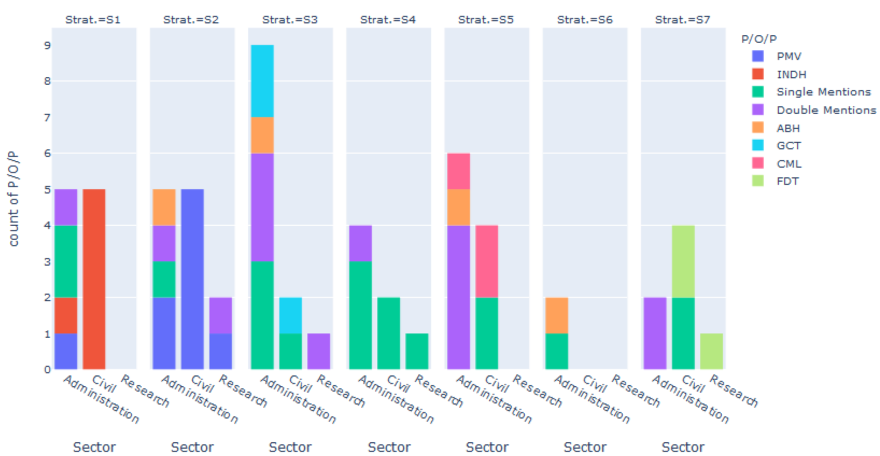

Figure 3.4: P/O/Ps participants named as examples for strategy implementation. For abbreviations see table S2

The mentions are highly diversified. Figure 3.4 is hence limited to mentions with more than three references. The other mentions are listed in table S2. The most frequently referred p/o/p is the Green Morocco Plan (PMV - Plan Maroc Vert), followed by the National Human Development Initiative (Initiative nationale pour le développement humain, INDH) and Basin Agencies (Agence du Bassin Hydraulique, ABH). Striking is the concentration of PMV for S1 and INDH for S2 and their absence for S3-7, whilst the ABH mentions are more dispersed. Moreover, INDH is almost exclusively *emergent* for citizens.

3.5.2 Emergent Strategies

The presented seven strategies for WEF challenges are not exhaustive. Thus, the participants were given the opportunity to bring forward own ideas for strategies in an open discussion. No restrictions on the definition of *strategy* were given. Mentioned strategies were thus *emergent*. The following three strategies received the greatest favor among the participants:

- **Promoting the culture of producing more water via new dams, small/large scale desalination and the different conservation methods.** The arguments behind this strategy is that Morocco as country shall promote fresh water provision and storage for both small scale and large-scale levels. E.g., newly implemented dams of large and small scale and also of collinear type could be easily maintained. It must be noted that technical solutions such as dams as well as desalination plants only work if enough water is available. The very limited and further diminishing local water supply the feasibility of these type of technical solutions is questionable

- **Creation of public institutions in charge of promoting rain water harvest and valorization.** It was emphasized that rain water harvesting is an ancient tradition in Morocco. Participants alleged that this technique, if implemented in a significant scale, would also serve for flood controls, reduce the pressures on the urban sewage systems, and conserve rain water from being lost. Rain water harvesting would also serve in mobilizing irrigation water for small urban/rural agriculture, and therefore increase domestic resilience.

- **Raising awareness at all levels of society about water conservation and valorization - "Creation of water council at local levels" .** Establishing water councils and institutions at the local level with institutional mandate to promote water use efficiency would help in conserving water and avoiding losses for any usage purposes.

Other debates focused on *construction of new dams on a larger scale (using solar collectors to prevent evaporation)*, *drip irrigation* and *crop choice*. The debate also raised the question of whether or to what extent the emerging strategies are still governance approaches rather than technical measures. In fact, all favoured *emergent* strategies with the exception of *foundation of water councils at local level* rather represent measures that were partly already discussed in the previous workshop than overarching concepts, i.e. strategies that try to govern the application of measures in an efficient way. This therefore fits in with the observations and criticism of for example Pahl-Wostl (2019); Ostrom and Cox (2010); Hoolohan et al. (2018) regarding the technical nature of many strategies.

3.5.3 Participatory Opinion Exchange: Strategy ranking for workshop-measures

A result of the II. Workshop was the preferential ranking of water saving measures of which the four favored measures to mitigate the WEF challenges were selected for the analysis of the governance strategies in Workshop III. At the III. Workshop, these four measures were used as the focus point for a mixed break-out group discussion on the question which of the presented strategies would be suitable to implement each of the measures. The break-out groups consisted of an - as far as possible - equi-distribution of PPs and citizens. Rankings of the suitability of the strategies for each measure were established (see table 3.2).

Table 3.2: Ranking of strategy aptitude for favored measures according to methodologies described in Chapter 3.4.3

Measures	S1	S2	S3	S4	S5	S6	S7
M1 Irrigation practices	7	2	5	4	6	1	3
M2 Efficiency of irrigation systems	7	1	3	4	2	5	6
M3 Efficiency of water distribution	7	6	4	3	5	1	2
M4 Crop choices	2	1	5	6	7	4	3
Average	5.75	2.5	4.25	4.25	5	2.75	3.5
Median	7	1.5	4.5	4	5.5	2.5	3

The ranking demonstrates that *S2 - Benchmarking* receives the highest appraisal among participants, however with a negative spike for measure M3 **Efficiency of water distribution**. The second most favored strategy for the measures, *Changing of organisation culture*, received a more uniform favor. Opposing to the high confidence that *S1 - Best practice guidelines* received prior to the discussion, its aptitude for most of the measures was judged almost uniformly low, with the measure *Crop choices* being the exception.

The results were openly debated in a grand discussion.

3.5.4 Strategy evaluation after participatory activities

Figure 3.5 demonstrates that the participants' opinion improved for all strategies after the their participation in the workshop activities. 84 times participants stated that their opinion was positively altered, whilst it was 22 times negative and 9 times neutral. Whereas the PPs verdict was almost entirely positive, the negative attributions originate mainly from citizens.

Especially S1 and S2 experienced just positive opinion alternation. The pattern for the other five strategies resembles each other with an equally low share of negative and neutral and attributions.

The participants reasoned their opinion alteration. For predominating 55 mentions, both the grand discussion as well as the mixed break-out debates

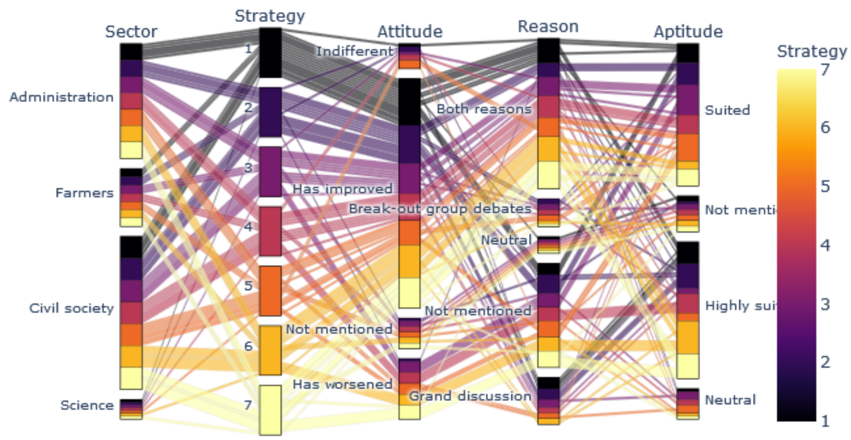

Figure 3.5: Participants' attitude and aptitude judgements after the activities

were quoted as main factors. Interestingly, participants with a worsened attitude towards a strategy named neither of the methods as reason for the decreased opinion.

Participants agreed almost uniformly on the aptitude of the presented seven strategies. 52 times strategies were evaluated as *suited*, 50 times even as *very suited*. Just eleven votes expressed a neutral sentiment for the strategies' aptitude. Surprisingly, not a single participant regarded a strategy as *unsuited* or *very unsuited*. Advantages that participants assume for specific sectors by an application of the proposed strategies are to be seen in Figure S5. Clearly, the economic-industrial (74 mentions) and the social-domestic sectors (79 mentions) are assumed to benefit the most from the strategies, whilst the presumed advantages for the agriculture (55 mentions) and the environment (46 mentions) drop behind.

The strategies have a varying impact on the differing sectors. S2 and S4 are especially assumed to generate positive impacts for the economic-industrial sectors, whereas S6 and S7 are supposed to have considerable positive impact for the social-domestic sectors of the MDV. Different evaluation patterns for citizens and PPs were not detected.

A similar approach was taken to reveal advantages participants assume for the application of the four favored measures of workshop II (see Figure S6).

The result here was rather uniform and ranged between 60 favorable mentions for Measure I and 46 favorable mentions for Measure III. Considerable impact of a single strategy on a measure is attributed for S1 on Measure I, S2 on Measure II and both S6 and S7 on Measure IV. Different evaluation patterns for citizens and PPs were not detected.

3.5.5 Post-workshop rapproachement

The workshop's approach was pragmatic and participatory and should serve, next to the other goals, to downsize the verto-horizontal disconnect in the realm of WEF challenges in MENA regions by discussing the application of certain strategic concepts. Participants were thus requested to judge after the workshop activities whether S1 to S7 beard said qualities to downsize the verto-horizontal disconnect.

Figure 3.6 demonstrates the participants' estimation regarding the respective strategies' aptitude to improve the quality of communication distributed over the sectors that assumed to benefit the most by the respective strategy. Multiple mentions were possible. A majority deems most strategies to be suited to do so.

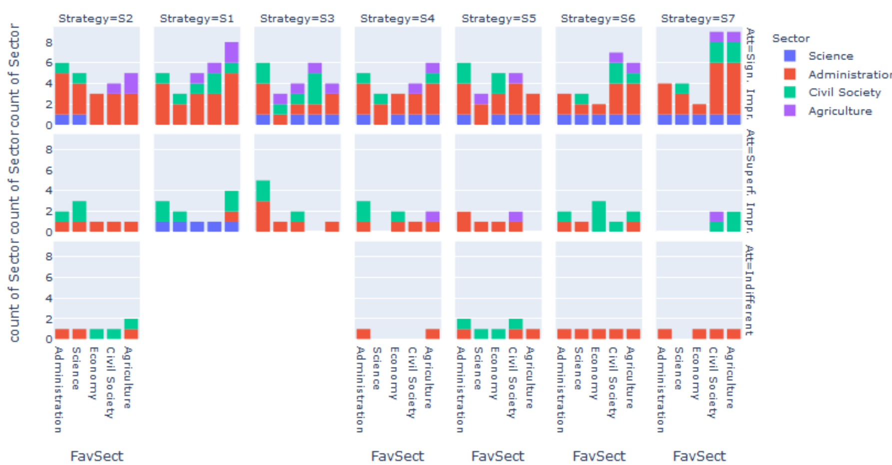

Figure 3.6: Communication improvement potential of strategies

PPs were generally more reluctant in attributing a strategy the potential to significantly improve stakeholder communication and only agreed for S4 and S5 (entirely) on the potential of a *significant improvement* in stakeholder communication. Citizens, on the other hand, were significantly more positive about the strategies' capacity to overcome the verto-horizontal communication gap. A notably high fraction of participants that were skeptical or indifferent exists just for S3. Apart from this, administration and agriculture were among the sectors whose communication participants assumed to benefit the most from the strategies.

Furthermore, participants should estimate, whether the strategies would be suited to dispel contradicting views and create a common ground for addressing WEF challenges between stakeholders. Multiple mentions were possible. The results are displayed in Figure 3.7. PP and citizen opinions diverge once more. PPs deem just S1 and - with restrictions - S6 to be suited to do so. The majority of citizens, on the other hand, was way more convinced, that strategies would serve to settle down opinion conflicts, with S1 and S2 being the exceptions. Again, administration and agriculture were among the sectors whose conflict potential participants assumed to be reduced due to the strategies.

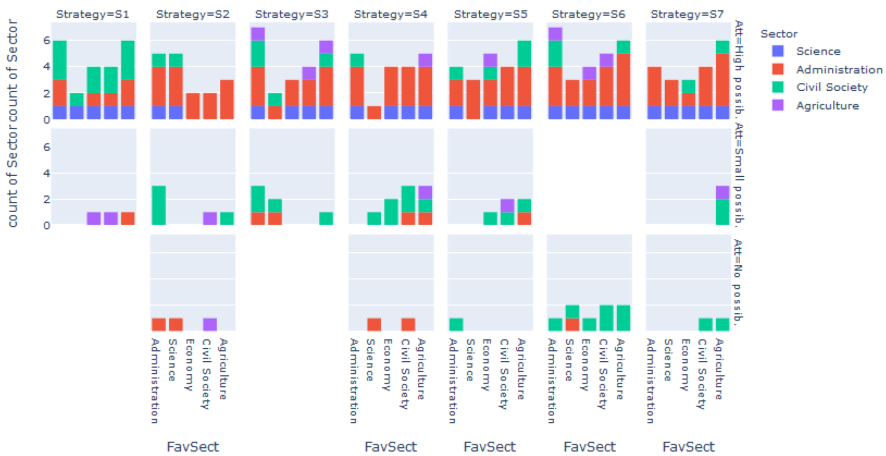

Figure 3.7: Contradiction and conflict resolution potential of strategies

When asked explicitly whether the workshop had improved the understanding of other stakeholders' problems and points of view, the majority of responses were consistently positive and connoted as *improved* or *significantly improved*, s. Figure 3.8.

However, the effect was strongest when PPs and citizens evaluated their own interest group. The highest gain in understanding attributed by other stakeholders was found for *Agriculture* (which, interestingly, was also attributed the highest loss of understanding) and *Administration*.

3.5.6 S8 - Water withdrawal charges

The example of water withdrawal charges was used to check, whether an equi-distribution of information in the environment of a *public action situation encounter* would be capable to indicate an assimilation in citizen and PP opinion in respect to a controversial strategy. If so, it would be a contribution to reduce the verto-horizontal disconnect by creating common ground.

Taking water withdrawal charges as an example, it was examined whether an equi-distribution of information in the environment of a *public action situation encounter* would create convergence between citizen and PP opinion with regard to a controversial strategy. After receiving information about the situation in Lower Saxony, participants were asked to state the amount of fee (in Moroccan

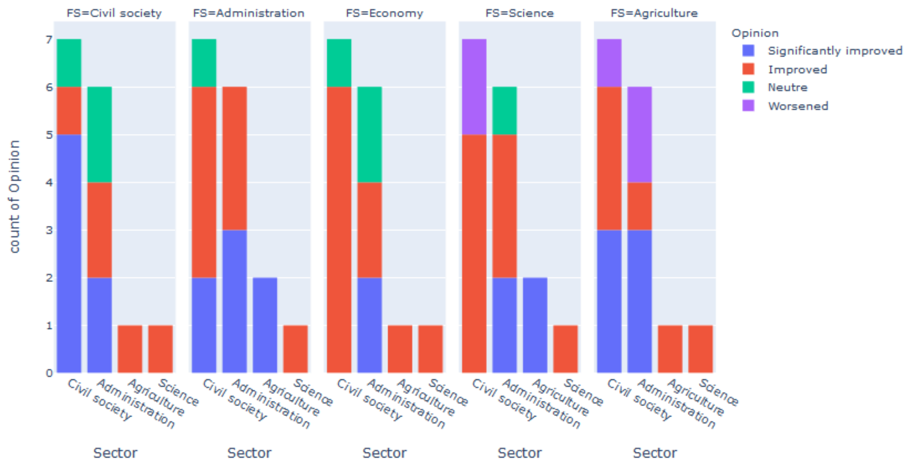

Figure 3.8: Participants post-activity opinion about the other sectors

Dirham (DH) per cubic meter) they deem suited as charge. This was done for each of the four sectors, the results are depicted in Figure 3.9. Participants were obliged to charge at least one sector.

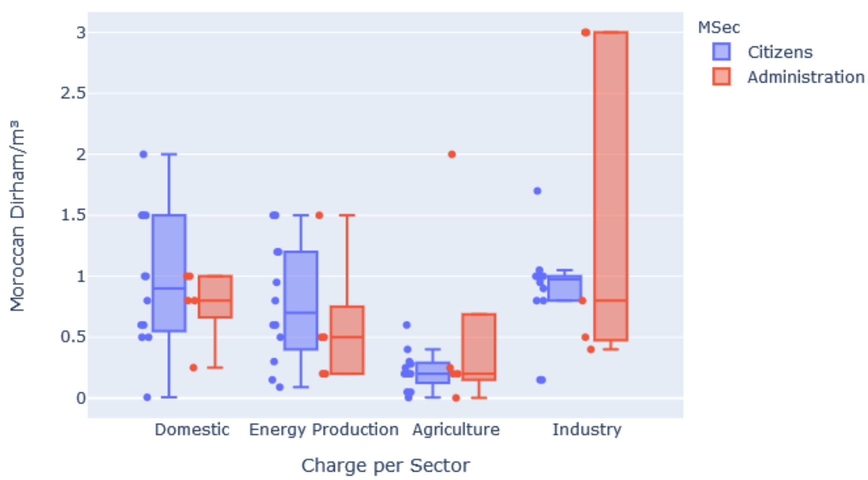

Figure 3.9: Water withdrawal charges participants would choose for each sector

Almost uniformly, participants opted to charge all sectors. Claims of citizens for charges were slightly higher than the ones of PPs. The highest median claim for a charge were 0.975 DH/m³ for the industry made by the citizen group. With 0.2 DH/m³ for the agriculture, the administration group made the lowest median claim.

According to Gawel and Bretschneider (2012); Neumueller (2000) there is a lower bound for water withdrawal charges below which no controlling and steering effect of the water withdrawal charge exists. Gawel and Bretschneider (2012); Neumueller (2000) reason that charges below said lower bound are economically not palpable for the target group.

Simultaneously, an upper bound is presumed. Said upper bound would impede the target group from further adjusting behaviour to the charge due to a respective limit in economic capability. The interval between those bounds is the *interval of effect*.

Graph 3.10 demonstrates the interval that participants presume for all sectors. It is almost identical for PPs and citizens and ranges between median values of 0.2 DH/m³ and 1 DH/m³.

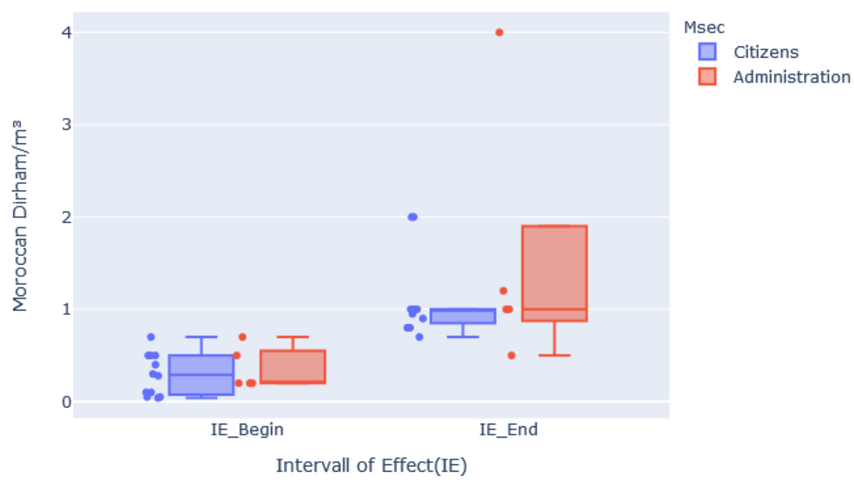

Figure 3.10: Interval of Effect participants would overall estimate

Furthermore, participants have a clear tendency towards adapting regionalized water withdrawal charges, in case it would be applied (graph S7). Moreover, participants are inclined to favor technical measures like water treatment plants, desalination facilities or the construction of new (hillside) reservoirs, when asked how they would spend the revenues gained from a hypothetical water withdrawal charge as shown by Figure S8. Alternatively, however, a smaller fraction of participants stated more governance influenced strategic goals (in Figure S9 when asked which kind of behaviour they would favor, if the revenues from the hypothetical water withdrawal charges would be earmarked subsidies (as it is partially the case in Lower Saxony (Quirin et al., 2015)).

3.5.7 The future objectives for the MDV

In a final remark, participants stated the three goals, that should receive paramount focus in MDV's near future. The variety of answers demonstrated by Figure 3.11 reveals a highly heterogeneous pool of opinions. *Touristic Growth*, *Protection of Water Resources*, *Industrial Production* the *Improvement of Education and Science*, each with seven mentions, as well as *Agricultural Production* and *Sustainable Technologies*, both five mentions, exhibit a striking quantity among the responses.

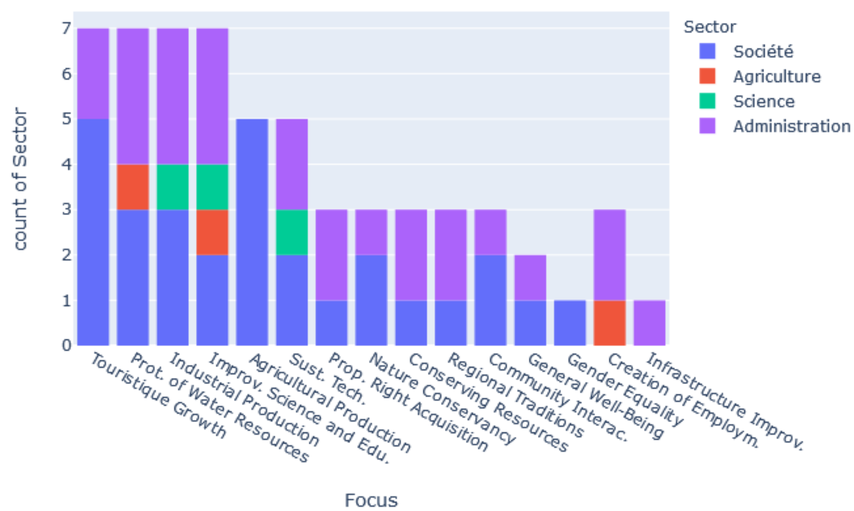

Figure 3.11: Focus points for the MDV according to the participants

3.6 Discussion

The data was analyzed for evidence to answer the research questions in regard to a strategy preference, the *emergence* of panacea-strategic thinking, and whether the extent of the verto-horizontal communication gap can be reduced. It is emphasized that due to the quantitative and organizational conditions of the workshop the results are of indicative character.

3.6.1 Strategy preference

The results of the methodology presented in Chapter 3.4.4(two SAWs and the inverted average of the BOG (with median as tiebreakers)) are presented in table 3.3. The scale of the numbers is not to be compared as it is not uniform.

Table 3.3: SAW, BOG (Break-out group) and final ranking of strategies preferred by participants according to methodologies described in Chapter 3.4.4

Strategie	SAW Sector	SAW S Ranking	SAW Measure	SAW M Ranking	BOG Measure	BOG Ranking	Ranking Accum.	Final Ranking
S1	6.271690215	2	6.659090909	2	1.25	7	11	3
S2	8.504761905	1	6.457792208	3	4.5	1	5	1
S3	5.14526426	6	5.957792208	5	2.75	5	16	7
S4	6.016431188	3	5.852813853	6	2.75	4	13	4
S5	5.86541078	4	6.362554113	4	2	6	14	5
S6	3.926216641	7	5.739177489	7	4.25	2	16	6
S7	5.737519623	5	8.05952381	1	3.5	3	9	2

Table 3.3 reflects the heterogeneous ranking and deciding conditions, that are typical for MADMs (Koksalan et al., 2013). Nevertheless, trends for favored strategies excel, which are: *S2 - Benchmarking*, *S7 - Tradition Including Platform Creation*, *S1 - Best Practice Guides*.

Striking in table 3.3 is the difference for the strategies *S2 - Benchmarking* and *S6 - Cultural Transformation*, whose ranking pattern is mirrored. Their pattern reflects a contradiction between a) the BOG-ranking that was obtained in a direct open discussion and b) the indirectly gained SAW-rankings. There might be an open/non-open-respond difference.

Various behavioral effects that are frequently found for open/non-open-respond differences might be the cause (e.g. social desirability (Noelle-Neumann, 1974)). The general conditions for the workshop did not allow to exclude such kind of effects. The detected contradiction is thus subject to further research.

The pattern of the rankings of table 3.3 roughly reflects the trends described in Chapter 3.5.1 in their tendency to either favor S1 or S2, which are more on the technical side within the range of presented strategies, or to support S7, which expresses the desire to actively include strongly (and traditionally) enrooted stakeholder groups of the MDV. This diverge between technical trended panacea and socially trended governance also becomes apparent within the surveyed *emergence*, which is discussed in the following section.

3.6.2 Emergence and top-down governance preference

As described in Chapter 3.3.4, *emergence* is understood as process that arises naturally or self-organized (Lumosi et al., 2019; Cundill and Rodela, 2012). Such processes or their underlying reasoning are hence deeply rooted in the *emergence*'s origin and are for the affected person highly considerable motives for acting and decision making.

Figure 3.4 and table S2 demonstrate the diversified character of *emergent* p/o/p.

Table 3.4 shows the verdicts of contemporary research analysis, that is in its majority not positive: Most of the prevailing p/o/p's are judged to be a) just superficially participatory and pragmatic, but in fact quite panacea top-down, or b) not successful in participation and pragmatism due to lack of efficiency, lack of support or political objections and even political opposition. Especially the most mentioned Green Morocco Plan and the National Human Development Initiative receive quite devastating verdicts. It needs to be noted that these are the results of the conducted assessment and do not reflect the stakeholder views.

Table 3.4: Evaluation of the major emergent p/o/p regarding their pragmatic and participatory character

p/o/p	Sources	Quotes	P&P verdict
INDH	(Bergh, 2012)	"contributes to the fragmentation and weakening of local (political) accountability"	(Officially) Appears to be P&P, but is in fact (quite openly) panaceas top-down
PMV	(Faysse, 2015)	"(…)the farm typology outlined in the original *PMV (author's note)* assessment was in fact inaccurate, and that, in practice, the Plan does not take the diversity of farms into account"	(Officially) Appears to be P&P, but is in fact (quite openly) panaceas top-down
GCT	(Faysse et al., 2010; Bouzidi et al.,2020)	"Farmer organisations that were set up to intervene in water management (…) were seen to be either inactive or to have weak links with their constituency; hence, the irrigation administration (…) continues to interact directly with farmers in a centralised way",(Faysse et al., 2010); "As a consequence, actors consider that the failure of past collective action is the farmers' fault, irrespective of the unfavourable context and the legacy of the past." (Bouzidi et al.,2020)	P&P approaches that succumb (quite openly apparent) to panaceas top-down
ABH	(Molle, 2017)	"These include the ineffectiveness of the water police, the failure by the ABHs to take action against people openly violating the law."; "(…)the 'aquifer contract' signed in the Souss basin in 2009 has so far largely remained a dead letter"; " (…) allow farmers to bypass the groundwater-use authorization process of the ABHs." "*ABH (author's note)* measures can be overridden by higher authorities and it is hard to escape the conclusion that there is limited political resolve to tackle overdraft for fear of curtailing the source of important social and political gains."	P&P approaches that succumb (quite openly apparent) to panaceas top-down
FDT	(Elmnrani, 2017)		Sparse info; due structure similarity to GCT, similar effect presumed
CML	(Majda et al., 2018)	"However, community participation is in its infancy in Morocco as was pointed out in our interview with one of the NPLC (National Program of Leishmaniasis Control) members. Given the absence of a study in Morocco evaluating the effectiveness of the community approach, we propose to implement a community participation approach to reduce vector density and determine its effect on the incidence of disease"	P&P approaches very initial/almost non-existent
FDA	(Faysse et al., 2016)	"The Agricultural Development Fund offers subsidies for the purchase of agricultural equipment. This fund existed before the Green Morocco Plan, but the latter allowed a sharp increase in subsidy rates. The main support is for small farms (less than 5 ha) (…)" "Moreover, many aquifers in Morocco are in a situation of overexploitation and the support tools for agricultural investment, particularly from the Agricultural Development Fund, take little account of this issue of overexploitation of the aquifers. "	Mixture of P&P enabling approaches and panaceas top-down (influenced by the PMV frame)

Whether the workshop participants were conscious of the researches' verdicts and whether they would agree or disagree to them remains a subject to be investigated. It is thus unclear, if the *emergence* of said programs happened based on or in spite of the characteristics that the cited research attributed to the p/o/p. Since the mentions were, however, given as a response to the theoretically clean designs of pragmatism and participation of the seven strategies (table 3.1), it is presumed that the p/o/p were *emergent* due to the perceived proximity to said strategies.

Nevertheless, the documented *emergence* in fact concerns p/o/ps that reflect, support or succumb to panacea top-down governance (Bergh, 2012; Majda et al., 2018; Elmnrani, 2017; Faysse et al., 2010; Bouzidi et al., 2020; Molle, 2017; Faysse, 2015; Faysse et al., 2016). It demonstrates thus the level of trust that participants and stakeholders from both PP and citizen side attribute to traditionally controlling and centralizing authorities (Marshall and Cole, 2017; Mo Ibrahim Foundation, 2019; Pacione, 2019).

As in Chapter 3.5.2, the participants' understanding of p/o/p is in part technical (table S2). Consciousness about this is nevertheless present among participants (Chapter 3.5.2).

A striking example for residing PP and citizen confidence in top-down technical approaches is the strategy (Chapter 3.5.2) request (formulated as a *emergent* strategy) for the erection of further small and large scale dams. Participants deem, as quoted in Chapter 3.5.2, the reservoirs as integrated, long-term solution with limited management expenses. Figure S8 joins this observation: Small/large scale reservoir construction was among the most cited profiteers of a hypothetical water withdrawal charge. This produces an interesting contrast and even conflict: According to Johannsen et al. (2016); Diekkrüger et al. (2010) the current WEF challenges of the MDV are indeed partly caused by misplanning or mismanagement of the reservoir El Mansour Eddabhi, that suffers from a severe reduction of storage capacity due to sedimentation.

Reservoir management globally trends to neglect sedimentation in reservoirs (Annandale, 2013) despite existing and in part long known management approaches (Kantoush and Sumi, 2017; Morris and Fan, 1998). This was, especially in earlier decades, caused by technical top-down planning (Kantoush and Sumi, 2017; Annandale, 2013; Schleiss et al., 2016). Sedimentation neglect and inappropriate management are therefore global threats to reservoir lifetime (Annandale, 2013). Nonetheless, the trust of planners, managers, PPs and citizens in reservoirs appears to be unweakened and optimistically biased by the assumption that the rather top-down reservoir implementation will have manageable WEF impacts (Schleiss et al., 2016; Landwehr et al., 2020).

The *emergence* of the reservoir approach within the workshop participant groups joins this observation and emphasis the presumption that technical panacea top-down approaches for WEF challenges still rank high for PPs and citizens of the MDV, especially when the background of the rather devastating situation of the El Mansour Eddahbi, where a tremendously high siltation endangers the operation goals of the reservoir, is taken into account (Johannsen et al., 2016; Diekkrüger et al., 2010). This pattern thus fits into the observation of Pahl-Wostl (2019); Ostrom and Cox (2010), who stated that technical solutions to overcome WEF challenges frequently bear the risk to become unspecified top-down actions, that lacks a holistic view, and produce undesirable and hardly revocable WEF impacts on the long run.

3.6.3 Downsizing the verto-horizontal disconnect

As described in Chapter 3.1 one of the research's main objectives was to answer the question whether a pragmatic and participatory approach could downsize the gap of the diagnosed verto-horizontal disconnect.

The results of table 3.5 show a convergence, i.e. a decrease of the differences between PPs and citizens, for five of the seven strategies, excluding just *S6 - Culture Transformation* and *S7 - Platform with Tradition Inclusion*. It is therefore concluded that vertical divergence between citizens and PPs was successfully downsized by the workshop activities.

Table 3.5: Discordance between PPs and citizens before and after the pragmatic and participatory activities according to methodology described in Chapter 3.4.6

Discordance	S1	S2	S3	S4	S5	S6	S7
Pre-P&P-Activity	0.38664	0.346391	0.47751	0.277572	0.386481	0.26469	0.333395
Post-P&P-Activity	0.30505	0.17873	0.190029	0.162447	0.204124	0.314024	0.469929

The impression is supported by the behavior that participants exhibit in respect to the controversial strategy 8.

Figure 3.9 and 3.10 depict median charges that resemble each other for citizens and PPs; be it for the *interval of effect*, be it for the hypothetical charges of the different sectors. Participants could have chosen to opt for hypothetical charges at a zero-level or auto-beneficiary investments. However, participants chose to range cost scales that they deemed acceptable for themselves in order to serve for a higher, altruistic purpose that shall ensure water security in the region. The fact, that the conclusions are derived from workshop data that was obtained in a non-open way (i.e. questionnaires) support, that group behavioral effects have not distorted them. From this, a reduced reluctance towards the concept of the water withdrawal strategy is deduced.

Furthermore, participants opted in Figure S8 and S9 for governance strategies of sustainable and regional-beneficiary character like water treatment plants and reduced water utilization in agriculture. From this, a constructive character of the results can be inferred. The same constructiveness is reflected in Figure S7.

Both the overall reduced reluctance towards this strategy, the similar PP and citizen cost scales and the apparent overall constructive response substantiate a higher vertical affinity between stakeholders and therefore a contribution of equi-distribution of information to a downsized verto-horizontal disconnect.

Aside from this, the horizontal disconnect between stakeholders appears to have been affected, as well. Participants of every sector emphasize that empathy and communication among sectors have been improved and conflict potential has been reduced (Figure 3.8, 3.6, 3.7) within the workshop due to the workshop activities.

It is thus concluded that the results of the present paper substantiate the presumption that pragmatic and participatory approaches downsize the unfavorable verto-horizontal disconnect in both directions. They therefore contribute significantly in managing WEF-challenges in MENA-regions in a more integrated and sustainable way.

3.7 Conclusion

The present paper substantiates the importance of pragmatic and participatory stakeholder inclusion in complex human-environment systems like the WEF-Nexus, especially in a local/regional context of the MENA region. After the workshop's public action situation encounter in the MDV-context the stakeholders reduced the verto-horizontal disconnect between PPs and citizens, which is a highly important step for strategy implementation as it creates a common ground for WEF-challenge strategy application.

The multi attribute analyses revealed a stakeholder preference for *S2 - Benchmarking*, *S7 - Tradition Including Platform Creation* and *S1 - Best Practice Guides* regarding the strategies' benefit for sectors and desired measure application in the MDV.

On the other side, the present paper demonstrated via emergence that the trust of both PPs and citizens in p/o/ps that support panacea solution is still quite high. Pragmatic and participatory approaches, on the contrary, were not very emergent and are not supposed to be enrooted in the MDV (and most likely also not in MENA, as similar approaches are scarce (Fayiah et al., 2020; Terrapon-Pfaff et al., 2018; Faysse et al., 2018)).

A similar observation of trust is made for rather top-down mid to grand sale solutions like reservoirs. The likelihood, that stakeholders are not aware of the panacea nature of p/o/ps and structures like reservoirs is given and this would, indeed, endanger the application of long-term sustainable strategies. However, the remains to be a subject for further investigation

All in all, the research fits into the observation of Pahl-Wostl (2019); Ostrom and Cox (2010) that the nowadays prevailing panacea solution in governance are not apt to account for the highly localized complexity of WEF-Nexus problems and that indeed pragmatic and participatory contexts offer a promising perspective for sustainable solutions for local/regional WEF-challenges in the MENA region.

3.8 Acknowledgements

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3.9 Declaration of Originality

We declare that this research is our own work except where there is clear acknowledgement and reference to the work of others. This research does not contain material that has already been used to any substantial extent for a comparable purpose.

CHAPTER

4

THE EFFECT OF OPTIMISM BIAS AND GOVERNMENTAL ACTION ON SILTATION MANAGEMENT WITHIN JAPANESE RESERVOIRS SURVEYED VIA ARTIFICIAL NEURAL NETWORK METHODOLOGIES

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Abstract

Reservoirs are installed as long-term assets to guarantee water and energy security for decades, if not centuries. However, the effect of siltation undermines reservoirs' sustainability because it significantly reduces the reservoirs' original capacity. The present paper attempts to evaluate the global reservoir siltation problem with the optimism bias theorem introduced by Kahneman and Tversky and applied to infrastructural mega-projects by Flyvbjerg and Ansar using artificial neural networks (ANNs) algorithms for large Japanese reservoirs. Japan possesses suitable long-term data and a legal directive concerning the sediment capacity siltation duration, which serves as a valid guide to check whether, over the past 100 years, engineers, planners and managers were capable of judging the sediment input correctly. Various ANN models were established to emulate Japanese reservoir siltation behavior. The networks demonstrate that reservoirs in Japan suffer from optimism bias. In contrast to the law, the dead storage volume of an average dam is supposed to reach capacity after 52 years. This finding joins the overall observation that mega-projects generally and globally suffer from optimism bias. The emulations were subsequently screened for a presumed influence of governance actions, namely, indicating plus monitoring and the change in the market competition situation. While reservoir siltation appears to continue regardless of the level of competition in public procurement, monitoring directives appear to have a considerable impact on improved siltation management, which demonstrates that dedicated governance action can significantly strengthen the sustainable behavior of key infrastructure elements such as reservoirs.

4.1 Introduction

Recently, hydropower has experienced a tremendous global construction boom. Fueled by the desire to create more active storage (Annandale, 2013), the number of installed dams is expected to more than double up to 2030 compared to 2010 (Zarfl et al., 2015). One of the reasons for this boom is siltation, which has led the gross reservoir volume per capita (Annandale, 2013) and the gross reservoir volume (Kantoush and Sumi, 2010) (as seen in figure5.1) shrink to 1970s levels despite the ever-growing number of reservoirs. This situation is a giant setback for sustainable long-term renewable energy generation and water supply security.

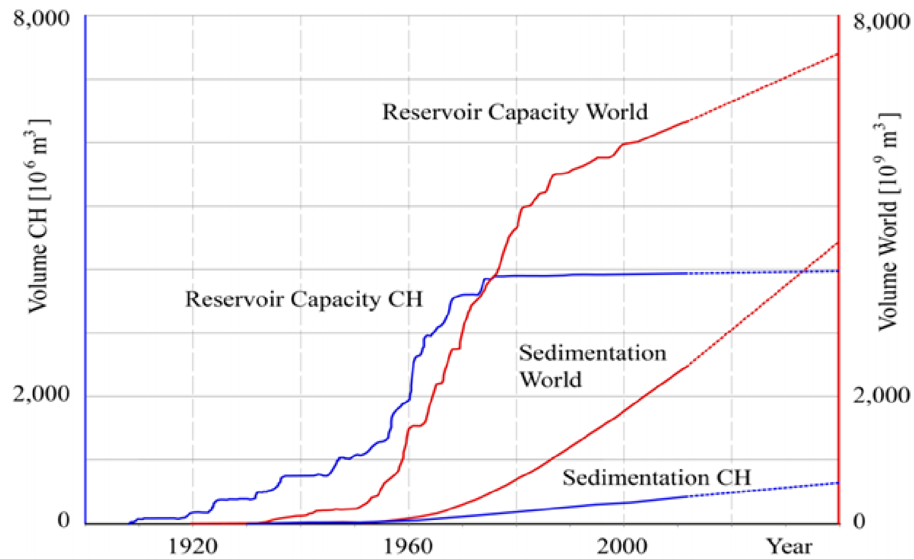

Figure 4.1: Assumed global (and Swiss) siltation development according to Kantoush and Sumi (2010)

Notwithstanding manifold siltation predictions and elaborate simulation models(Omer et al., 2015; Simoes and Yang, 2006; Zeleke et al., 2013; Ghimire and DeVantier, 2016; Hao et al., 2017), the global development insinuates that planners, operators and practitioners struggle to predict both the sediment inflow and yield reservoirs correctly. Consequently, the implementation of suitable management strategies for siltation remains a challenge (de Vente et al., 2013; Yang, 2013; Schleiss et al., 2016; Kantoush and Sumi, 2017), which prevails regardless of the respective environment, climate, society and technology level Annandale (2013); Basson (2009); Schleiss et al. (2010). It appears that planners, operators, managers and constructors are overly optimistic, i.e., they are biased by the so-called optimism bias (Schleiss et al., 2016).

Said optimism allows responsible persons to underestimate risks while over-estimating their own capacities. By doing so, they neglect the given data and experience of already installed projects of the same or similar kind (Ansar et al., 2014; Flyvbjerg, 2006, 2016). This theory was initially developed by Tversky and the Nobel prize-winning Kahneman (Kahneman and Tversky, 1979; Fox and Franz, 1987).

Siltation data are, however, globally scarce (Schleiss et al., 2016). Few authorities monitor sediment in a regular, overarching manner, except in Japan (Kondolf et al., 2014; Auel et al., 2016), which makes it an ideal country for data-driven experience analysis.

Because there is increasing pressure on reservoirs due to (unforeseen) siltation, retrospective amendment methods play a key role in sediment management (Annandale, 2013; Kantoush and Sumi, 2017; Schleiss et al., 2016). Said methods are manifold and often technical in nature; however, they are not generally applied (Kantoush and Sumi, 2017; Morris and Fan, 1998).

On the other hand, governance measures exist. Similar to technological solutions, their use case application is also limited (Pahl-Wostl, 2015), which is indeed startling, as it is observed that governance measures can have a high impact within the water-energy-food nexus (WEF nexus) (Pahl-Wostl, 2015). Reservoirs, as a junction between energy production and water supply (for, e.g., crop production), belong to the WEF nexus. As one of its aims, this study seeks to find evidence that substantiates the effect of governance on sediment management.

Siltation is a non-linear time series process (Annandale, 2013). An emergent tool for non-linear data analysis and non-linear data emulation are artificial neural networks (ANNs), whose advantages include comparatively rapid applicability and a vast use case flexibility (Gamboa, 2017). Thus, they are this study's method of choice to detect evidence of optimism bias and governance effects.

The present paper seeks to identify evidence that substantiates the presumption of optimism bias behavior in sediment management and planning.

To verify whether optimism bias is indeed persistent in siltation prognosis and reservoir management, the outside view introduced by Kahneman and Tversky and data analysis are key features (Kahneman and Tversky, 1979; Ansar et al., 2014).

The subsequent methodologies will produce general results, i.e. this analysis does not account for every single dam in a highly specific manner −it is acknowledged that there are huge individual differences. Nevertheless, if the Japanese reservoirs were regarded as an entity, the produced results will give worthwhile insights about large scale reservoir sustainability.

4.2 Methodology

4.2.1 Selection of an Optimism Bias Reference

Optimism bias detection requires a reference class (Flyvbjerg, 2006; Ansar et al., 2014; Kahneman, 2011) to establish a needed outside view(Kahneman and Tversky, 1979; Kahneman, 2011). More than often, (large scale) projects were established and carried out by the project team itself or by people related to the project judging on project data. This is the so-called inside view(Kahneman and Tversky, 1979). It is often quite sophisticated and accounts for the own resources, capacities and skills. However, what is unaccounted for are the so-called *unknown unknowns*, which are impossible to perceive if one resides inside of a system (Kahneman, 2011).

In doing so, large scale infrastructure projects are more than often affected by cost overshoot or by a project completion way beyond the initial schedule (Flyvbjerg, 2016; Ansar et al., 2014; Flyvbjerg, 2006). An outside view is thus needed. It is provided by already completed projects of a similar class, i.e. a reference class is needed (Kahneman, 2011; Kahneman and Tversky, 1979). The reference class serves as a great indication, where projects are going to head in the future.

Translated to the case of Japanese reservoir siltation, the projects, i.e. reservoirs, that have already been installed and their sedimentation data are the very key to create a reference class. They are supposed to indicate quite neatly the overall siltation state of reservoirs after a certain period according to Flyvbjerg (2016); Kahneman and Tversky (1979). To judge whether the outside view and the inside view diverge (i.e. whether an optimism bias exists), a siltation planning marker is needed.

Reservoirs have an installed siltation capacity, which is often congruent with its *Dead Storage Volume* (Kantoush and Sumi, 2017). This volume lies below the reservoir outlet and cannot be actively used for water management. However, it serves as siltation buffer to guarantee the full usage of active storage over a planned period of time. An insufficient siltation capacity is seen as a clear threat to operation security and a long reservoir lifetime (Rakhmatullaev, 2010; Kantoush and Sumi, 2017).

In this study, lifetime is defined as the termination of the initially intended operation purpose due to siltation; it does not necessarily equal a 100% siltated reservoir. By no means lifetime is equal to the ratio of siltation capacity to the mean annual sediment inflow. The siltation capacity situation is, however, a very good proxy to judge whether the intended operation lifetime or longevity will be kept in the future.

The time of operation for reservoirs must be estimated, designed and planned by managers, practitioners and engineers. A divergence from these plans is a clear indication of siltation underestimation. If siltation underestimation is systemic for reservoirs, it becomes a general bias, namely, an optimism bias.

For most of its reservoirs, Japan introduced (*Showa 32* - 昭和 32 年) a directive in 1957 that demands one hundred years of minimum durability for the siltation capacity (*Kasen Hobou Gijutsu Kihon* - 河川破防技術基準 - Norm for relevant techniques against destructive river basin management, NTDM), according to Okano et al. (2004).

The NTDM norm is the marker of this research. A general divergence of siltation in the sediment capacity volume in Japanese reservoirs from the legal siltation goal is seen as an indication of optimism bias in sediment prognosis and management.

4.2.2 Base Data

The base data originated in 2015 (*Heisei 27* - 平成27年) and were provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Public Works Research Institute (PWRI). In total, 1006 dams are included (as shown in Figure 4.8). Dams of different purposes, types and sizes (small: <1m m^3, medium: >1m m^3, large: >10m m^3; very large: >100m m^3 of total storage volume [this definition is made for Japan and not internationally applicable]) are incorporated. Hence, the data reflect the general character of Japan's reservoir landscape. The data comprise the siltated volume, inactive storage capacity, and active storage capacity along with general data such as inauguration or river basin affiliation. Of these, 141 dam sets were not directly usable because they were incomplete. Stochastic measures were undertaken to utilize them (Figure 4.2).

As the data did not separate active and dead storage siltation, the assumption was made that the whole siltation occurred in the reservoirs' dead storage volume. It was regularly observed, though, that active storage siltation initiated far earlier and fiercer than scheduled, i.e. before the complete dead storage volume was exhausted (Reza Rahmanian and Banihashemi, 2012; G.R. Basson, 1999). Consequently, this research represents a non-realistic optimal state from the reservoir management perspective. The actual reduction of active storage must be considered to be fiercer than suggested in this study (Kantoush and Sumi, 2017).

If arranged by the inauguration year, the base data represent a time series that allows us to draw conclusions about general siltation management performance in Japan. The terms *general* or *average* refer in this context to siltation performance behaviour that is to be derived from the Japan overarching conglomerated data by the ANNs. The emulations shall thus produce a siltation development archetype that is typical for Japan based on the available data (approach).

To do so, the data were transformed for ANN purposes and streamlined to the desired key information: 1. The year of reservoir inauguration and 2. the reported lake siltation versus the dead storage volume.

4.2.3 ANNs

For the given data, a non-linear relation is presumed. ANNs are considered a good tool for the analysis, pattern detection and data emulation for this type

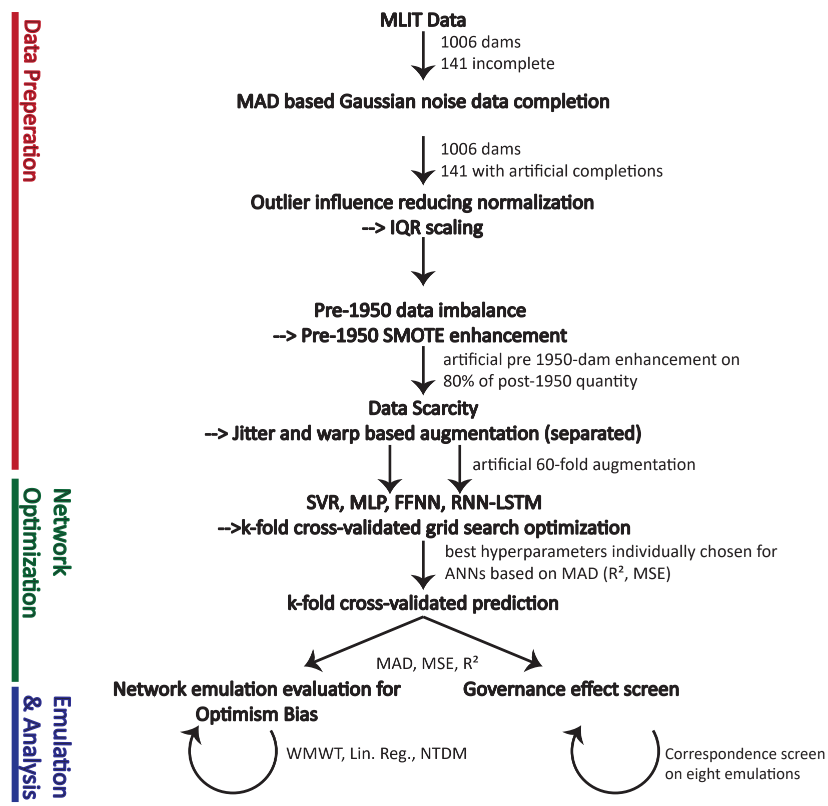

Figure 4.2: Flowchart of the methodological process

of data behavior (Gamboa, 2017; Schmidhuber, 2014; Michelucci, 2018). First, simple network attempts were already conceived and approached throughout the 1960s, 1970s and 1980s. A breakthrough of the ANN methodology was reached in the recent decade due to a significant increase in CPU and GPU computation power (Chellapilla et al., 2006), which allowed ANNs to grow in size and solve complex problems. Due to the amount of computed neurons and the necessary CPU/GPU power, the ANN method is described as a brute force approach (Perez, 2017) or reinforcement learning (Zhang et al., 2018a).

A well-trained ANN is capable of emulating, forecasting or even creating realistic results based on limited or incomplete non-linear data (Schmidhuber, 2014; Michelucci, 2018). This situation is given for the Japanese (or every other country's) siltation case.

ANNs are thus a viable tool to emulate a generalized contemporary state of siltation for reservoirs of certain ages in Japan. The ANN mass data analysis and will thus give feedback and insights on the Japan wide overall state of reservoir siltation and the presumed deviations from the actually planned siltation state.

This allows to draw conclusions on large scale large infrastructure management of a country and hence the (not-)perpetuation of sustainability according to the World Commission on Environment and Development (1987) definition.

ANNs consist of different layers of weighting entities, so-called neurons. Their objective is to emulate a variety of known relations that are presented to them based on training data. The neuron entities iteratively receive and process the data within different kinds of internal connections whilst perpetually updating their weights. Performance is checked on a separate validation test set. The neurons are designed to reduce the asserted deviation between the known training data relation and the results of the own emulation of the prior iteration by a certain, determined degree (Schmidhuber, 2014; Michelucci, 2018).

As the relation of training and validation data is known, the emulation accuracy on test and validation data is used as a guidance on network performance. In a concluding network performance check, the ANNs capability to generalize on new data is surveyed by an iteration on the hitherto unseen test data (Schmidhuber, 2014; Michelucci, 2018).

To suit ANN demands, the data need to be randomly split into a training part and a testing part. In this study, this split is done by k-fold cross-validation. The technique separates the complete data into k entities, out of which k minus one form the training part. The left k-sized fraction forms the test set used for network validation. In the next iteration, the network is trained and tested on another k-set. This methodology equals out extremes caused by arbitrary chosen splits. Moreover, it guarantees the usage of the full test set. It is also used for optimization purposes (s. next chapter) (Jiang and Chen, 2016).

ANNs face several issues that reduce their performance or contort results. Among them are overfitting (Zhang et al., 2018a; Allamy, 2014) and underfitting (Allamy, 2014), data scarcity, the need for normalization, data imbalance and outlier influence (Khamis et al., 2005). These issues were addressed using methods such as dropout (Park and Kwak, 2017), augmentation (jitter (pure Gaussian noise) and warp (Gaussian noise on Bezier-Curves))(Um et al., 2017; Le Guennec et al., 2016; Velasco et al., 2018; Xiao and Xu, 2012), synthetic minority oversampling technique (SMOTE) (Fernández et al., 2018), interquartile range (IQR) scaling (Mizera et al., 2004) and median absolute deviation (MAD) (Gorard, 2013) based Gaussian noise data completion. The complete process is shown in Figure 4.2. The jitter and warp-based augmentations were carried out separately and displayed discretely in the results. Warp is used to produce better results, as the enhancement follows a more continuous process.

4.2.4 Selection of Network Hyperparameters

Several ANN types are applicable for time series emulation, including support vector machines for regressions (SVR) (Nisbet et al., 2017), feed forward networks (FFNN) or multilayer perceptrons(MLP) (Michelucci, 2018), and long short term memory recurrent ANNs (RNN-LSTM) (Michelucci, 2018). MLPs and FFNNs resemble each other quite lot. Thus, their emulations are expected to be similar.

SVRs and MLPs were applied via SKlearn libraries (Pedregosa et al., 2011), FFNNs and RNN-LSTMs were constructed using TensorFlow and Keras libraries (Abadi et al., 2015).

ANNs succumb to hyperparameters that regulate them. These hyperparameters have tremendous influence on their performance (Michelucci, 2018; Nisbet et al., 2017). To select the optimal operation environment, the best-performing hyperparameters were chosen using an iterative k-fold cross-validation grid search process (Jiang and Chen, 2016). The optimization guidance was formed using R^2, MAD and mean squared error (MSE) as metrics. Thus, MAD was the prime criterion because it is comparatively robust to outlier distortion in a non-linear environment (Gorard, 2013). The other metrics were used if they improved by 15% after a cross-validation iteration. The optimized values were chosen as hyperparameters, which can be seen in table 4.1. The emulations themselves were also carried out in a k-fold cross-validated manner. Overall, eight emulations were produced.

Table 4.1: Overview of k-fold cross-validated grid-searched hyperparameters. Please refer to the text for more details on abbreviations, etc.

	Network Specific Optimized Setups			
Hyperparameter	SVR	MLP	FFNN	RNN-LSTM
Learning Rate	-	0.0006	0.015	0.004
Batch Size	-	128	100	256
Optimizer	-	Adam	Nadam	Adam
Loss Function	-	-	mae	logcosh
Activation	-	tanh	relu	tanh
Epochs	-	automatic	15	12
Dropout	-	-	10% per layer	50% per layer
Hidden layer setup	-	500/150/70/25/1	500/150/200/50/1	250/120/10/1
k-fold emulation	4	4	8	3
C	1.20E+02	-	-	-
Gamma	1	-	-	-
Epsilon	0.004			
Kernel	rbf	-	-	-

4.2.5 Network Metrics

Over- and underfitting performance were originally considered as a measure to select the best-performing two ANN types, since over- and underfitted ANNs are not capable to generalize appropriately on new data. Such networks either emulate the testing data in an overly exact ragged fashion (overfitting) or fail to react to each type of new data (underfitting) (Allamy, 2014; Zhang et al., 2018a). The selection process was planned to be carried out via the analysis of R^2 performance. Due to reasons stated in the chapter "Metrics' Validity" in the Discussion, no best-performing network was selected and all four are displayed as main results.

Their evaluation is carried out via MSE, R^2 and MAD. The focus lies on the latter, as it is more robust against the influence of outliers (Gorard, 2013), which is important considering the generalization approach of the study. In nonlinear relations, however, the metrics have a limited significance. This is discussed later in "Metrics' Validity".

Furthermore, a mere linear regression was computed from the original data to test whether major deviations between the elaborated ANN approach and the linear regression exists. The linear regression thus serves as an indication of whether the ANN approach is actually worthwhile.

4.2.6 Identification of an Optimism Bias

The networks were evaluated regarding optimism bias in a way similar to prior research by Ansar et al. (2014). The Wilcoxon-Mann-Whitney Test (WMWT) was used to identify whether the optimism bias hypothesis should be rejected (W. Corder and I. Foreman, 2014).

4.2.7 Identification of Governance Impact

One of the aims of this research is to substantiate a presumed sustainable effect of governance on sediment management.

The research focuses on two elements: 1. legal and administrative directives and 2. the economic environment. For the prior, regulatory means for indication and monitoring were chosen as prevalent. For the latter, the procurement competition situation was selected.

A substantiation is assumed if an ANN-identified period of reduced siltation accumulation coincides with periods of governance intervention in Japan. Those intervention periods are to be identified.

Indication and Monitoring

The implementation of the *Kasen Hobou Gijutsu Kihon* - 河川破防技術基準 (Norm for relevant techniques against destructive river basin management; NTDM) (Okano et al., 2004) in 1957 (Shouwa 32 - 昭和 32) was a major incident that changed the approach of indication and monitoring for reservoirs within Japan. Another contribution of that epoch is a revision of the NTDM. It enforces systematic monitoring and legal pressure and is reported for the middle of the 1960s (Okano et al., 2004). The years around 1957 form a period of special interest.

Competition

Following Flyvbjerg and Ansar, a non-competition situation in public procurement leads to a higher observed optimism bias and thus to irregularities (such as inappropriately managed siltation) in negative effects for mega-projects. Competition should be seen as a contribution towards an aim-based project management (Ansar et al., 2014).

In Japan, several events were highly influenced by competition environment in public procurement economics (Fujii, 2012). Prior to the second World War the *Shimei Kyousou* (指名競争) was prevalent. Business collusion between the state as tenderee and its contractor, the powerful Japanese *Zaibatsu* (財閥), was a daily occurrence. Competition-induced pressure for performance increases was de facto non-existent (Fujii, 2012).

In 1947 competition was pushed by the *Shiteki Dokusen no Kinshi oyobi Kousei Torihiki Kakuho ni kan suru Houritsu (Dokusen Kinshi Hou)* - 私的独占の禁止及び公正取引確保に関する法律 (独占禁止法), the so-called Antimonopoly Act. Due to a lack of control and political unwillingness, however, the effect was limited (Kinoshita et al., 2008). The rather non-competitive state continued to be in effect for public construction tendering, as the 1981-Shizuoka incident demonstrated. It evolved around the ministry of construction and its then minister Saitou Shigeyoshi, who had to step back after large scale bid-rigging was revealed to the Japanese public (Fujii, 2012; Kinoshita et al., 2008). Kinoshita (2012) confirms that during this era the minority of tenders were subject to real competition.

The situation changed in 1994 with the *Koukyou Jigyou no Nyuusatsu･Keiyaku Tedzuzuki no Kaiyen ni kan suru Koudou Keikaku* - 公共事業の入札･契約手続の改善に関する行動計画 (Public procurement: Plan for the improvement of contraction procedures). ,which was the most important step in the public procurement economy since 1900(Kinoshita et al., 2008). The years around 1947 and 1994 are thus important time period for improved competition. Among both events, 1994 had a higher influence.

4.3 Results

The produced emulations reveal a uniform picture. The siltation is fiercer than the design demanded by law (Okano et al., 2004). The median years for a certain fraction of siltation can be derived from table 4.2. The divergence between some of the emulations is a matter for the discussion part.

For 100% dead storage siltation the median of the eight simulations lays in the year 1964, i.e., reservoirs built in that year are generally expected to have lost their complete dead storage volume. For 50% siltation, the median emulation expects the year 1985, i.e., dams constructed in that year are assumed to have lost half of their dead storage volume. All emulations reach 150% siltation of dead storage, some far more.

Three ANN types show similar behavior with several distinguishable phases,

Table 4.2: Median siltation of dead storage emulations

Dead Storage Siltation	Jitter				Warp				Median
	SVR	FFNN	LSTM	MLP	SVR	FFNN	LSTM	MLP	
50%	37	33	17	26	38	38	24	24	29.5
100%	54	52	48	41	53	51	51	38	51
150%	101	81	88	49	81	80	87	53	81
200%	-	-	-	72	104	109	-	70	-

which will be described below. LSTM emulations present an excerpt with a rather continuous siltation growth emulation.

In contrast, the scale of three ANN types is rather uniform, with MLP types being the exception. MLP types project a considerable fierce emulation of siltation growth. The entire range of emulations can be found in Figure 4.3. The variability that the generalized ANNs deem likely is denoted by ragged parts and the boldness of strokes.

The metrics for most emulations show uniform patterns in table 4.3. MLP emulation metrics diverge from the rest, which corresponds to their different scale. LSTM metrics also differ slightly from FFNNs and SVRs. The discussion will address the implications of these metrics.

Table 4.3: Metrics of the eight emulations

Metric	Jitter				Warp			
	SVR	FFNN	LSTM	MLP	SVR	FFNN	LSTM	MLP
MAD	0.3912	0.3754	0.4136	0.6521	0.3793	0.3654	0.4023	0.6385
MSE	9.99	10.07	9.893	9.154	10.14	10.22	10.05	9.238
R^2	0.0127	0.0074	0.0246	0.0965	0.0139	0.0099	0.0259	0.1011

From Figure 4.4 it is evident that most emulations differ significantly from a mere linear regression. In fact, the linear regression indicates a far fiercer siltation rate for the reservoirs than the ANN emulations. Only the MLP emulations range in the order of the same increment.

The concordance (in shape and scale) of the emulations insinuates that a mere linear regression cannot reflect the complex non-linear behavior of a long-time reservoir siltation, i.e., that the ANN methodology is worthwhile.

The subtraction of the NTDM from the network emulations reveals oversiltation behavior, which is demonstrated by the equation below (OS=Oversiltation, PS=Projected Dead Storage Siltation in %, DS= Dead Storage Siltation demanded by the 1957 Directive in %).

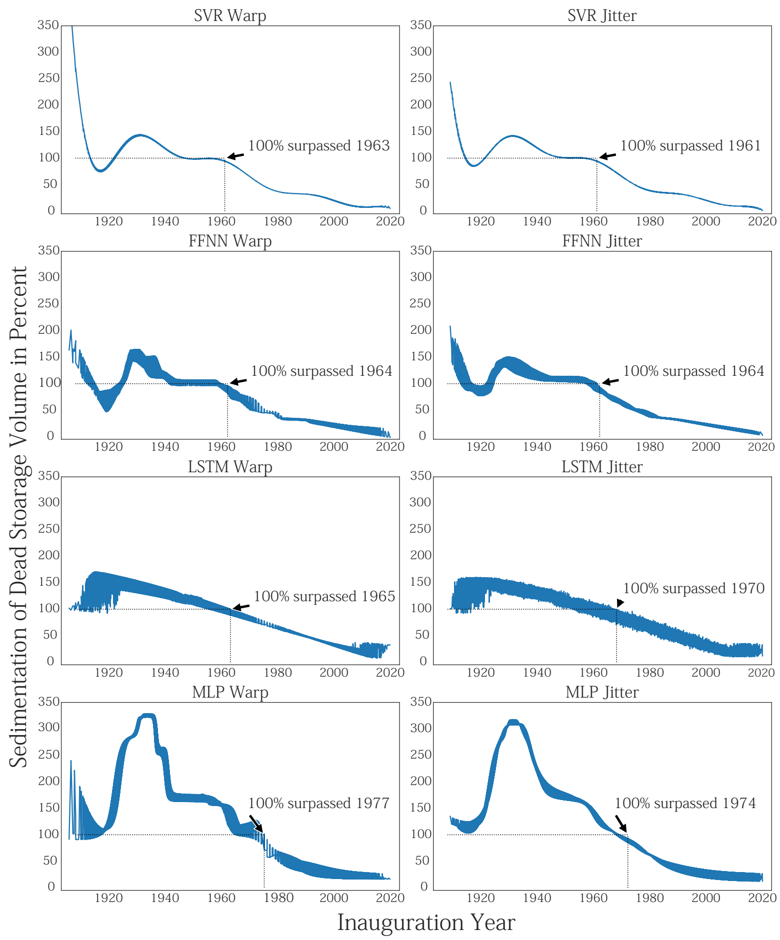

Figure 4.3: Eight emulations based on four ANN types and two augmentation methodologies

$$OS = PS - DS_{2015} \tag{4.1}$$

Oversiltation is prevalent for all types of emulations, as shown by Figure 4.6. Based on the shape characteristics, it can be sub-classified into five different phases whose names are based roughly on historic or Japanese epochs. An exemplary breakdown can be consulted in Figure 4.5. The enumeration is carried out from present to past from right to left on the graph.

1. *Heisei Antei* - 平成安定.Heisei Stability: Constant oversiltation, ranging around 20% up to year 1980

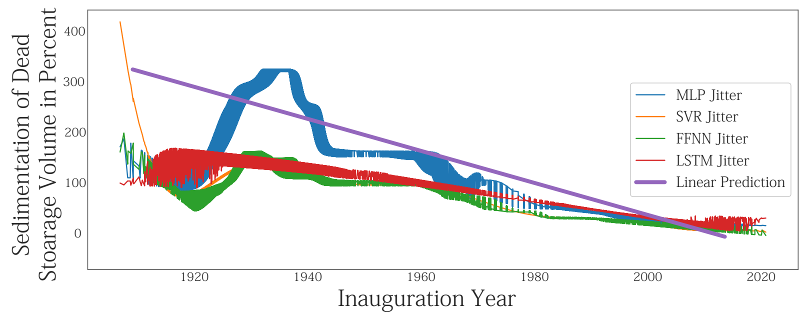

Figure 4.4: Warp augmented emulation in comparison to a linear regression

2. *Shouwa Kakou* - 昭和下降.Shouwa Drop: A drop of oversiltation towards the Heisei-level, initiated from the end of the 1950s/beginning of the 1960s.

3. *Shouwa Antei* - 昭和安定.Shouwa Stability: Rather constant level of oversiltation from the mid-1940s onward that ranges approximately 60% for FFNN and SVR (and LSTM) and 100% for MLP.

4. *Sekai Sensou Kakou* - 世界戦争下降. A drop of a very steep (MLP) or rather smooth nature during the time of the second World War.

5. *Taishou Aimai* - 大正曖昧.Taishou Ambiguity: Values of high ambiguity, roughly around the Taishou time.

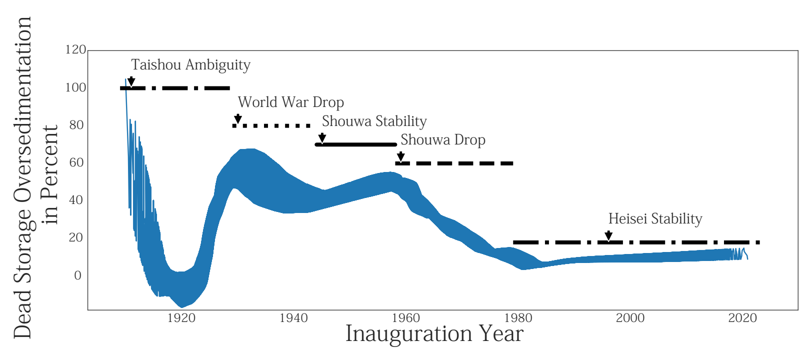

Figure 4.5: The Jitter-augmented FFNN emulation and the identified periods of siltation behavior

Two periods reflect a time of significant oversiltation reduction, i.e., an improvement of siltation treatment and management. One coincides for all emulations of a characteristic shape with one of the three periods of identified governance intervention: The NTDM laws were established when the Shouwa

Drop was triggered. as seen in Figure 4.6. It is an indication of the contribution of governance to improved siltation management.

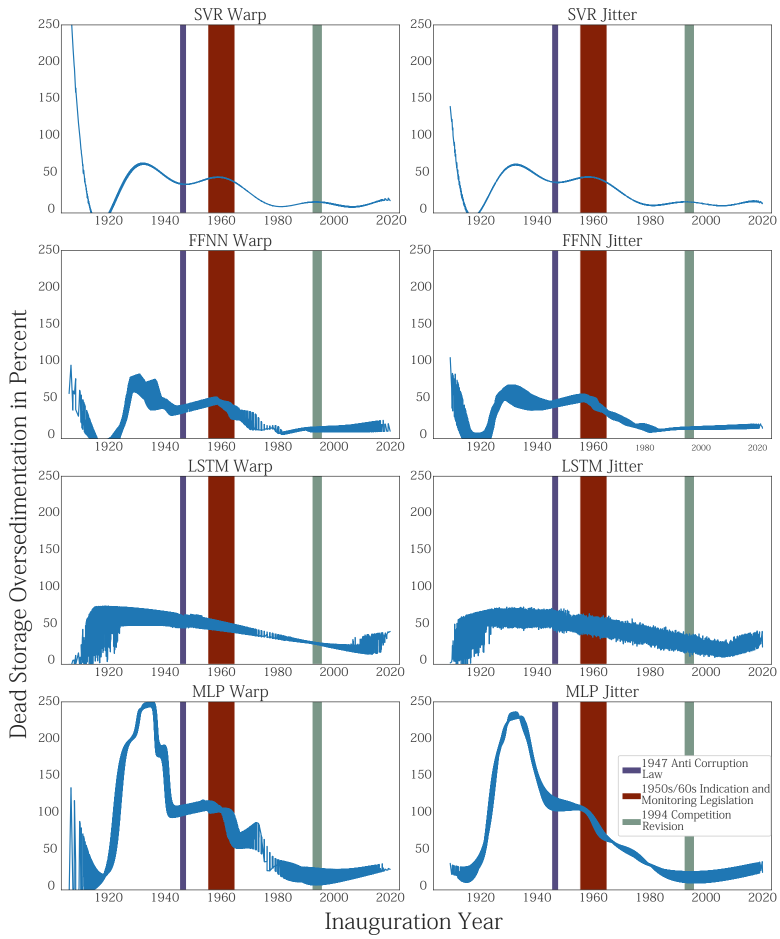

Figure 4.6: Degree of oversiltation in all emulations and coincidence with governance interventions with a potential impact on siltation management performance

Because siltation of the general Japanese dam lies constantly beyond the 1957-demanded NTDM range, the presumption is that planers and managers were not capable of meeting its standards, including in recent projects, as Figure 4.6 demonstrates.

A comparison in Figure 4.7 with the siltation values of six coincidentally elected reservoirs that were recorded between 2000 and 2017 shows furthermore that a rough quite a concordance in shape and behaviour with the Jitter augmented FFNN and thus with the five identified phases. It is emphasized that the data of the six reservoirs (provided by the PWRI and MLIT) were not included in the ANN base data, i.e. that it is unknown to the ANN. This shows that the ANN have achieved quite a good generalization on Japanese dam behaviour given that the selected dams originate from different regions, are different size and inaugurated in different decades.

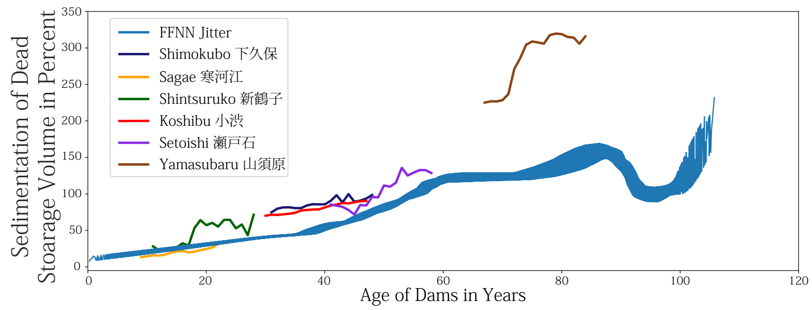

Figure 4.7: Comparison of observed and coincidentally selected dead storage siltation values with emulated dead storage values.

It is furthermore assumed that the reservoir projects would not have been permitted if authorities, planners and managers were not convinced to meet the NTDM. Therefore, systematic conduct of high optimism can be derived.

The WMWT supports this by assigning every ANN emulation statistical significance with p-values close to zero and U-values far less than the critical U (e.g. Warp-augmented FFNN: p=2.39e-182 and U=32774307 far less than the U_crit=57623970.173) when compared to a distribution of values that meets the NTDM. The null hypothesis is consequently rejected.

This means, the emulated values and values that meet the NTDM are not from the same distribution and they indeed represent the outside view demanded by Kahneman and Tversky (1979); Flyvbjerg (2016). As already demonstrated in Figure 4.6, the values are way higher than NTDM values. Hence, emulated values derived from real data are not expected to meet the NTDM. This happens - as the WMWT shows - in a statistically significant and systematic manner. With regard to fullfilling the NTDM, it must be assumed that generally both siltation was underestimated and the own skills overestimated. This implies that siltation management suffers broadly from optimism bias.

4.4 Discussion

The ANN emulations differ in shape and range, which should be expected, as they are influenced by different build-ups (Michelucci, 2018; Nisbet et al., 2017). Interestingly, many similarities exist among the emulations. At some points, differences were noted where they were not expected.

4.4.1 The divergence of MLPs and LSTMs

The difference in the scale of the MLP emulation towards the other network emulations is striking. The shape, however, resembles that of SVRs and FFNNs. Originally, FFNNs and MLPs were rather similar, as their internal structures are based on a very similar feed-forward approach (Makrem et al., 2016). The different results can most likely be explained by two features: the Dropout (Park and Kwak, 2017) and the Loss (Li et al., 2018), that were missing in the applied SKlearn architecture for MLPs.

The LSTM shape divergence has to be attributed to the completely different build-up of LSTM-Neurons, which are designed to have a memory function (Michelucci, 2018). LSTMs are thus more robust to short-run deviations compared to ANNs (Shah et al., 2018). However, it is not entirely clear why this phenomenon causes the observable effect.

4.4.2 Metrics' validity

As seen in table 4.3, MLPs appear to outperform the other ANNs in terms of the MSE and the R^2 whilst being themselves on a rather mediocre level in absolute terms. However, the significance of such metrics needs to be discussed.

First, it is important to emphasize that the comparability between them is partly limited because the emulations succumb to differently randomized k-fold splits of the same base data.

Second, according to Spiess and Neumeyer (2010); Alexander et al. (2015); Pontius et al. (2008) the validity of both R^2 and RMSE is questionable in non-linear environments. Achen (1990) argues that their whole significance is rather limited. Nevertheless, they are used quite regularly (McKellar and Lu, 2003).

In this study, a non-linear ANN emulation, especially R^2 is viewed under a completely different angle, namely as an indication of overfitting. Under non-linear deep learning circumstances, an optimum value for both R^2 and RSME is not desirable, which would mean an absolute fit and thus non-generalization, i.e., overfit. In contrast, low performance indicates a complete no-fit and thus an underfit. Acceptable but imperfect R^2 and RMSE results are hence desirable. Because this approach is not entirely verified, no ANN type was omitted during this study due to supposed overfitting likeliness.

Overall, the MAD is seen as a more valid indication of a good emulation fit. Although the MAD basically resembles the MSE, the focus on the median reduces outlier influence. Emulations that do not cover all outliers receive a better score, as reflected in table 4.3; they appear to be more generalized (Gorard, 2013) and thus of higher scientific value.

4.4.3 Impact of augmentation technique

Although the emulation results differ, a clear recommendation on which tech nique produces better results cannot be drawn. Other than expected, Warp-augmented emulations are neither clearly distinguishable nor bear significant advantages to Jitter-augmented emulations. The demonstrated closeness of results, however, points towards the robustness of the ANN approach.

4.4.4 The Taishou Ambiguity and the World War Drop

Data imbalance has a negative impact on ANN performance (Michelucci, 2018) which exists for pre-WWII data. Almost no reservoirs were constructed during that period of time as Figure 4.8 demonstrates. Their data footprint is thus amplified compared to that for dams in other epochs.

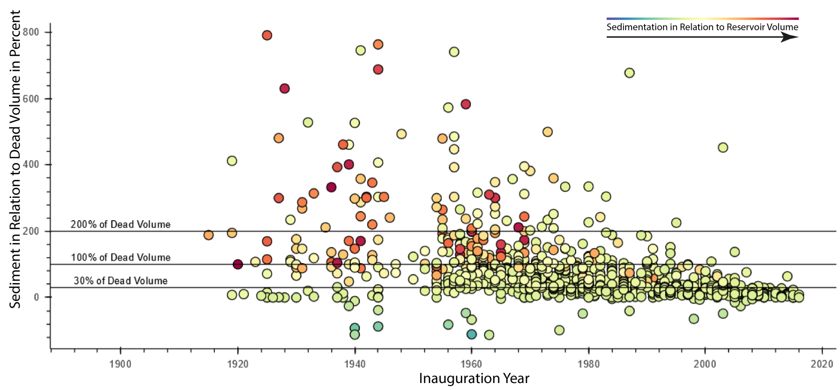

Figure 4.8: Distribution of siltation in Japanese reservoirs based on 2015 data

Several measures were undertaken to reduce the data imbalance of pre-WWII data. Though improvements were made, the Taishou Ambiguity demonstrates that these imbalances were not overcome entirely. A rapid decline and a subsequent rise in dead storage siltation is observable for many emulations.

This finding should not be taken literally; rather, it is a directional cue. If the drop around 1920 were omitted, most emulations return to the prior magnitude of oversiltation, as seen in Figure 4.6. The emulation graphs would then comply with the asymptotic saturation behavior of siltation found in other research (Annandale, 2013; G.R. Basson, 1999; Kantoush and Sumi, 2017).

4.4.5 Japanese reservoir situation and intrinsic Optimism Bias

According to table 4.2 the dead storage capacity for a contemporary dam is likely to be consumed after 51 years of operation. Figure 4.8 demonstrates the intensity of the Japanese reservoir situation.

With respect to the inauguration distribution seen in Figure 4.9, this finding is quite alarming. The majority of large and very large dams will soon reach 100% capacity of dead storage volume, whilst the medium and small dams will likely do so within the next 5 to 10 years.

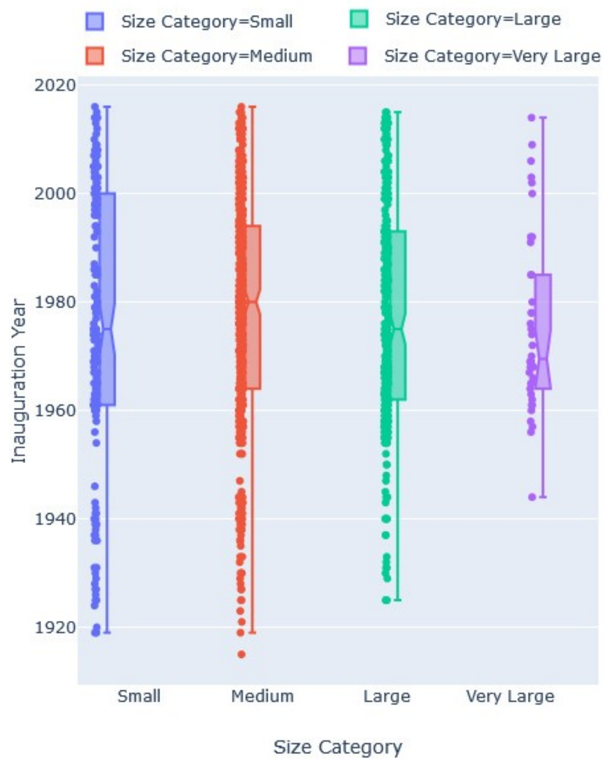

Figure 4.9: Distribution of dam inaugurations and corresponding medians; Small=1975, Medium=1980, Large=1975 , Very Large=1969

As mentioned in the introduction, it is needless to say that this analysis does not account for every single dam −there are huge individual differences. Nevertheless, if the Japanese reservoirs were regarded as an entity, the result is a reason for profound concern regarding reservoir sustainability.

Because Japan is among the best-performing countries in terms of siltation management(Kondolf et al., 2014; Auel et al., 2016), this finding implies an even more somber situation for other countries.

The fact that the dead storage volume is comparatively small in relation to the rest of the reservoir, as shown in Figure 4.10, means no relief for two reasons:

1. As (Kantoush and Sumi, 2017; Annandale, 2013; Basson, 2009) imply, the siltation of a reservoir does not occur entirely within the dead storage but also affects a considerable fraction of active storage. Because this study found that in most reservoirs, siltation is greater than expected, and the fraction of reduced active storage is also assumed to be greater than expected.

2. The dead storage serves as a marker. If clear laws such as the NTDM

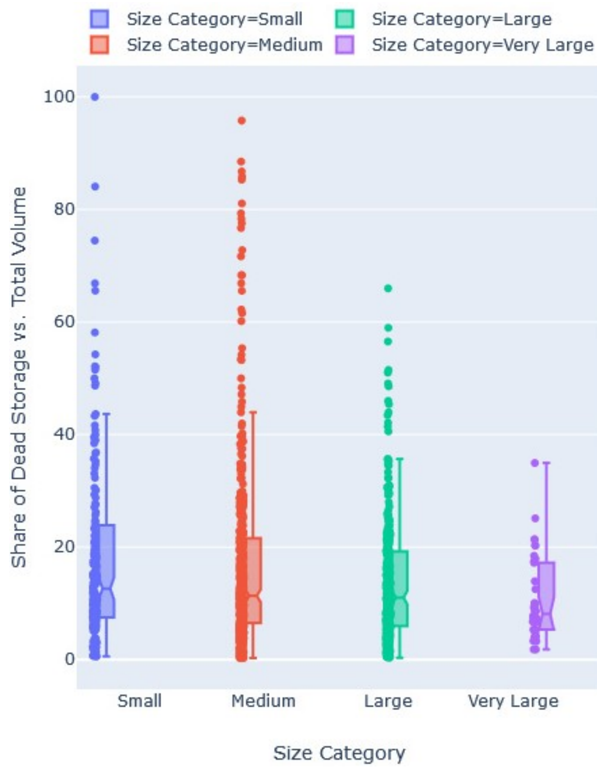

Figure 4.10: Fraction of dead volume in relation to total reservoir volume with corresponding medians. Small=12.63%, Medium=11.35%, Large=11.03%, Very Large=8.13%

cannot be kept, the implication can be made that longevity is a feature that will not be kept. Thus, it can be inferred that most reservoirs are not constructed in sustainable way, but rather in an optimistic way due to the inside view (Kahneman, 2011). They are optimistically biased. As Japan is a pioneer in sediment management (Sumi, 2015; Kantoush and Sumi, 2019; Kondolf et al., 2014), we can assume that the effect is stronger throughout the rest of the world, which implies that the global sustainability of reservoirs is not guaranteed.

4.4.6 The Impact of Governmental Action

The introduction of the Antimonopoly Act and, hence, the effect of induced competition on siltation in 1947 is not clearly perceivable. Moreover, almost no effect is noticeable for the enforcement of competition in 1994. Among the 1947 and 1994 acts, the latter has a higher impact on competition according to Kinoshita et al. (2008) Thus, it seems likely that competition has had no impact on siltation performance.

Two assumptions regarding this lack of effect might serve as explanations. First, siltation is of minor significance for the economic competition that companies the planning and construction of reservoirs, which fits the globally observed pattern (Annandale, 2013). If long-term siltation performance is a decisive criterion in reservoir economics, far more new dams would include new measurements for reduced siltation (Kantoush and Sumi, 2017; Zarfl et al., 2015). Second, the laws were of minor efficiency, as indeed reported by Kanda and Fujii (2017): Dumping in pricing and business collusion are still quite established in Japan. Thus, competition might not have any effect because it is still nonexistent.

Contrarily to the competition, the introduction of strict obligations regarding monitoring and indication seem to have influenced sediment performance. As Figure 4.6 shows, the oversiltation reduction during the Shouwa Drop coincides for all of the emulations quite neatly with NTDM introductions after 1957. Following the upper observations, the perceived governmental effects must be assigned to the obligations made for siltation monitoring and indicating.

4.5 Further thoughts on the variety of siltation conditions

The hydrological variability caused by climate changes have an increasingly high impact on water and sediment inflow to the reservoir. One of the main shortcomings in global siltation management is the implementation of a widespread quantification of flow and sediment rating curves under the changing climate.

Annandale (2013) explained that the magnitude and spread of the anticipated increase in hydrologic variability is not known. Therefore, it is necessary to make both engineering and governmental decisions to deal with the uncertainties.

Kantoush and Sumi (2019) explained that there are various challenges regarding dam management due to climate changes and increased number of flood peaks. A periodical monitoring for reservoir siltation before and after every flood event is seen as a very valuable practice. In case of increased reservoir siltation, an immediate intervention or an upgrading of the dam facilities is necessary to recover the original dam functionality and to ensure reservoir capacity is recommended to cope with the fiercer flooding events. Moreover, physical processes of sediment transport and siltation as well as upgrading and retrofitting effects on reservoirs of high age need to be understood to guarantee a sustainable long-term operation,

Measuring the benefits and costs of siltation management improvement for the development of a sustainable infrastructure is often difficult. However, it is unavoidable that siltation management needs to perform economic feasibility studies for the methodologies in consideration.

The long-term economic, ecologic and social costs and benefits of asset management in coordination with changes in dam and downstream should be in perspective during decision making (Annandale, 2013; Kantoush and Sumi, 2019). This should extend to include a thorough assessments of climate change impacts on aging reservoirs and the determination of ecosystem responses to new reservoir projects as well as to the ongoing loss of reservoir functionality of already installed dams. Moreover, critical studies to demonstrate the social dimension of man-made reservoir interventions is inevitable for adequate sediment management.

From the authors point of view and based on the findings regarding the optimism biased management, (new) concepts and methodologies should be conceived a priori to design intergenerational, sustainable, self-supporting rehabilitation systems for river basins with man-made reservoirs. Further research is needed to guide the future management for aging Japanese and global reservoirs to optimize and reflect both the huge investment decisions that will have to be made and the legacy that reservoirs mean for the future generations.

4.6 Conclusions and Outlook

The applied ANN methodologies serve as a powerful tool for detecting optimism bias. The latter likely exists in Japanese reservoirs because compliance with the NTDM directive could not be assured. This observation implies that planners and practitioners hazard the consequences consciously or unconsciously.

Although reservoir designers have powerful techniques at hand, they should consider a more conservative approach for dam longevity and actively seek for outside view information like the ones of the present paper.

Neither the omission nor the implication of *competition* as a tool led to a different sediment behavior during Japanese history. It is thus presumed that the reforms had limited effects and/or that siltation does not play a decisive role in the consideration of public procurement. This behavior is assumed to be global. In this case, it would have a devastating impact on the worldwide long-term sustainability of reservoirs.

Emphasis is given to the power that governmental approaches possess, if applied correctly (with an incorporated outside view). Countries and regions that are confronted with sediment issues should take this power into consideration. Dams constructed under such new directives might not produce the highest revenue in the short run but will most certainly do so in the long run.

Moreover, active management and refurbishment methodologies should be undertaken to guarantee and ensure the longevity and sustainability in already constructed and new dams, as Kantoush and Sumi (2017); Auel et al. (2016) demonstrate.

Upcoming in-depth multivariate, multi-time series approaches with ANN methodologies will produce more detailed findings which should be useful in gaining more insight for siltation management in Japan and worldwide.

4.7 Acknowledgements

Important stakeholders played crucial roles for the formation of the research; among them the *Kyuushuu Denryoku* - 九州電力 (Kyushu Electric Power Company), the *Kokudo Koutsuu Shou* - 国土交通省 (Japanese Ministry of Land, Infrastructure and Transport, MLIT), the *Domoku Kenkyuu Sho* - 土木研究所 (Public Works Research Institute, PWRI), which offered kind and competent support of knowledge and data. Moreover, the *Nihon Gakujutsu Shinkou Kai* - 日本学術振興会 (The Japanese Society for the Promotion of Science, JSPS) and the Sievert Stiftung promoted the Japanese-German exchange and research by equally kind and important financial and organizational support. The author expresses his deep gratitude to all named organizations.

4.8 Declaration of Originality

I declare that this research is my own work except where there is clear acknowledgement and reference to the work of others. This research does not contain material that has already been used to any substantial extent for a comparable purpose.

CHAPTER

5

DEMONSTRATION OF THE IMPACTS OF ANTI-SEDIMENTATION TECHNIQUES ON JAPANESE RESERVOIR SILTATION VIA MASS DATA ANN ANALYSIS

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Abstract

Reservoirs have been installed as long-term assets to guarantee water and energy security for decades, if not centuries. However, the effect of siltation undermines reservoirs' sustainability because it significantly reduces the reservoirs' original capacity. Extreme events such as typhoons, floods and droughts are posited to have extreme impacts on sediment inflow and deposition in reservoirs. The same holds true for ISMTs (implemented sediment management technologies), such as dredging, spilling and bypassing. However, the large-scale analysis of their effects on reservoir sedimentation progression, recovery and development was not feasible due to data scarcity and technological restrictions. The present paper closes this information gap by conducting a GRU (gated recurrent unit) neural network analysis of 1224 Japanese reservoirs, for which the sedimentation, local precipitation, extreme events and IMSTs were monitored between 2000 and 2017. The network reveals the beneficial impacts of dredging, spilling and bypassing. The results also demonstrate the potential of smart management and improved monitoring for sedimentation threat abatement. Thus, foresighted engineering and dedicated governance action in flood and drought scenarios can significantly strengthen the sustainable behaviour of key infrastructure elements such as reservoirs.

5.1 Introduction

The number and capacity of hydropower sites and reservoirs are expected to increase within the next decades (Annandale, 2013). For example, Zarfl et al. (2015) assume that the global quantity of installed dams will double from 2010 to 2030. Although a non-negligible number of proposed reservoirs will not be completed, the overall reservoir trend consists of constant or disproportional growth (Özge Can Dogmus and Nielsen, 2019).

A partial explanation for the construction boom is the increasing siltation in already inaugurated dams, which has reduced the gross reservoir volume per capita (Annandale, 2013) and the gross reservoir volume (Kantoush and Sumi, 2010) (as shown in Figure 5.1) to the level of the 1970s despite the ever-increasing number of reservoirs. This is a giant setback for sustainable long-term renewable energy generation and water supply security.

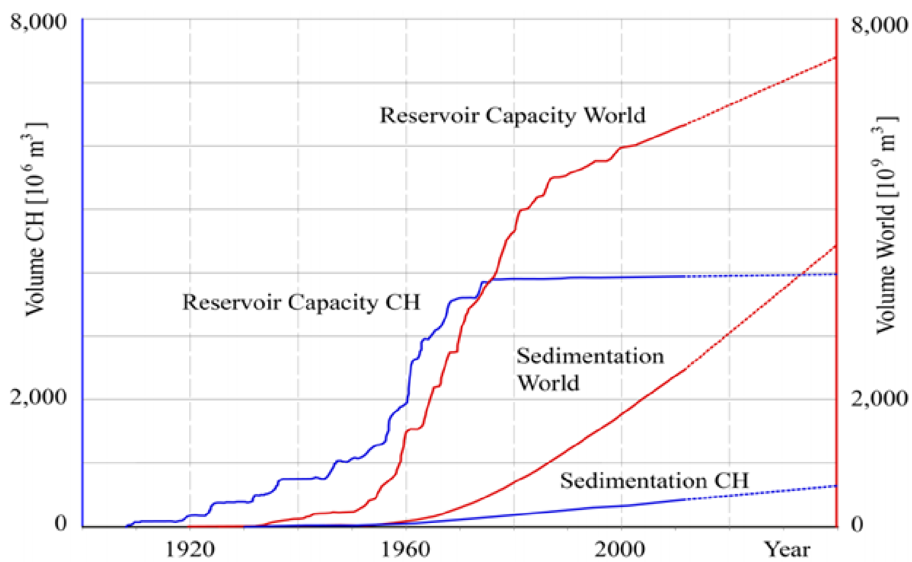

Figure 5.1: Assumed global (and Swiss) siltation development according to Kantoush and Sumi (2010)

Studies show that planners, operators and practitioners underestimate the siltation threat whereas they overestimate their own capacities, namely, that reservoir sedimentation management suffers from optimism bias (Landwehr et al., 2020; Flyvbjerg, 2016; Annandale, 2013; Schleiss et al., 2016). Thus, it is no surprise that the implementation and analysis of suitable management strategies remain challenging (de Vente et al., 2013; Yang, 2013; Kantoush and Sumi, 2017) despite the availability of manifold elaboration prediction and simulation approaches (Omer et al., 2015; Simoes and Yang, 2006; Zeleke et al., 2013;

Ghimire and DeVantier, 2016; Hao et al., 2017). This scenario prevails regardless of the environment, climate, society and technological level and threatens the designed functionality of reservoirs worldwide Annandale (2013); Basson (2009); Schleiss et al. (2010).

This is alarming, as reservoirs are a junction infrastructure element of the WEF (water-energy-food) nexus, namely, via crop production or hydro-electricity. Hence, reservoirs and their sedimentation are also crucial factors in the realization of highly interlinked sustainable development goals (SDGs) (United Nations, 2015; Zhang et al., 2016a; Pousse and Latouche, 2018).

Various technological, management and governance approaches to amend, reduce or reverse sediment accumulation in reservoirs are applied globally to a scant degree compared to the global gross reservoir volume (Morris and Fan, 1998; Kondolf et al., 2014; Pahl-Wostl, 2015; Kantoush and Sumi, 2017, 2019; Sumi, 2015; Morris, 2020). Moreover, the analysis of these approaches has been restricted to local or regional studies (Haregeweyn et al., 2013; Pandey et al., 2016; Wild et al., 2016; Adeogun et al., 2018; Velásquez-Castro et al., 2016) of single or a few reservoirs due to a lack of siltation data (Schleiss et al., 2016). The same holds true for events that are beyond human control, namely, forces majeures such as floods, typhoons or earthquakes, which have substantial impacts but the analysis of which is typically local or regional (Lee et al., 2006; Vanmaercke et al., 2014; Wang et al., 2018; Stähly et al., 2019).

Large-scale, long-term and data-driven studies regarding reservoir sedimentation management and event impact have proven to be challenging in recent decades, as few authorities monitor sediment in a regular, overarching manner. Thus, the general effects of these approaches remain unclear.

One of the exceptions in data monitoring, however, is found in Japan, which is also one of the leading countries in applied sediment management (Kondolf et al., 2014; Auel et al., 2016; Kantoush and Sumi, 2017).Japanese data collection regarding siltation is comparatively vast in terms of both time and extent (Landwehr et al., 2020).

However, siltation is a nonlinear time series process (Annandale, 2013). An emergent tool for nonlinear data analysis and nonlinear data emulation is artificial neural networks (ANNs), the advantages of which include comparatively rapid applicability and vast use case flexibility (Gamboa, 2017).Recurrent neural networks (RNNs), which include long short-term memory (LSTM) and gated recurrent unit (GRU) variants, are especially suitable for surveying complicated and intertwined time series processes (Elsworth and Güttel, 2020; Fu et al., 2016; Petneházi, 2019).

By utilizing RNNs, the present paper seeks to derive evidence from the Japanese dataset that various events or management technologies and actions have retraceable impacts on reservoir siltation. The study aims at deducing these effects from a big long-term data picture to obtain generalized results that might be applied or reproduced globally. In most countries of the world, data are scarce; hence, to pursue global reproducibility, this paper attempts to obtain improved results but not maximum confidence with a highly reduced data input.

The pursuit of general results implies that this analysis does not consider every single dam in a highly specific manner –it is acknowledged that there are huge individual differences. Nevertheless, if the Japanese reservoir variety is regarded as a reflection of the reservoir variety in many countries or regions, the produced results will provide worthwhile insights into reservoir sustainability.

5.2 Methodology

The data suffer from ambiguity due to the influence of other parameters. Figure 5.2 presents the absolute sedimentation in comparison to the age of the respective reservoirs. It also shows occurrences of (natural) events or implemented sediment management technologies (IMSTs) (from now on, event categories is used to refer to both). Information on how the event categories influence sedimentation is difficult to derive in these few and partially contradictory examples. Thus, additional information is needed; tools that can extract information from a complex web of data, such as ANNs, are also needed.

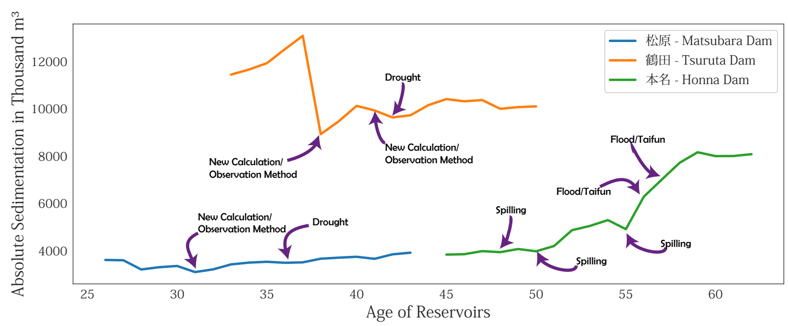

Figure 5.2: Three examples show that the impacts of event categories on siltation are not (easily) derivable from a few examples

The objective of the ANN methodology in the present paper is to train a network on a reduced set of data that also includes notifications on event categories, namely, to extract a variable that insinuates what the network has learned regarding each event category.

In this study, the network aims at learning the execution of flexible and generalized hindcast emulations on the siltated whole volume for each reservoir. To do so, the network must learn data characteristics for each category of input data. This also holds true for the event categories.

The study shall finally display whether the event categories exert general reducing or enforcing effects on siltation in reservoirs. To do so, a semi-randomly selected variance of original reservoir data is modified and retested on the ANN hindcast emulations with modified data. The modification regards solely the event categories. The deviation from the hindcast emulations with original event category data creates the desired variable. A simplified outline is presented in Figure 5.3.

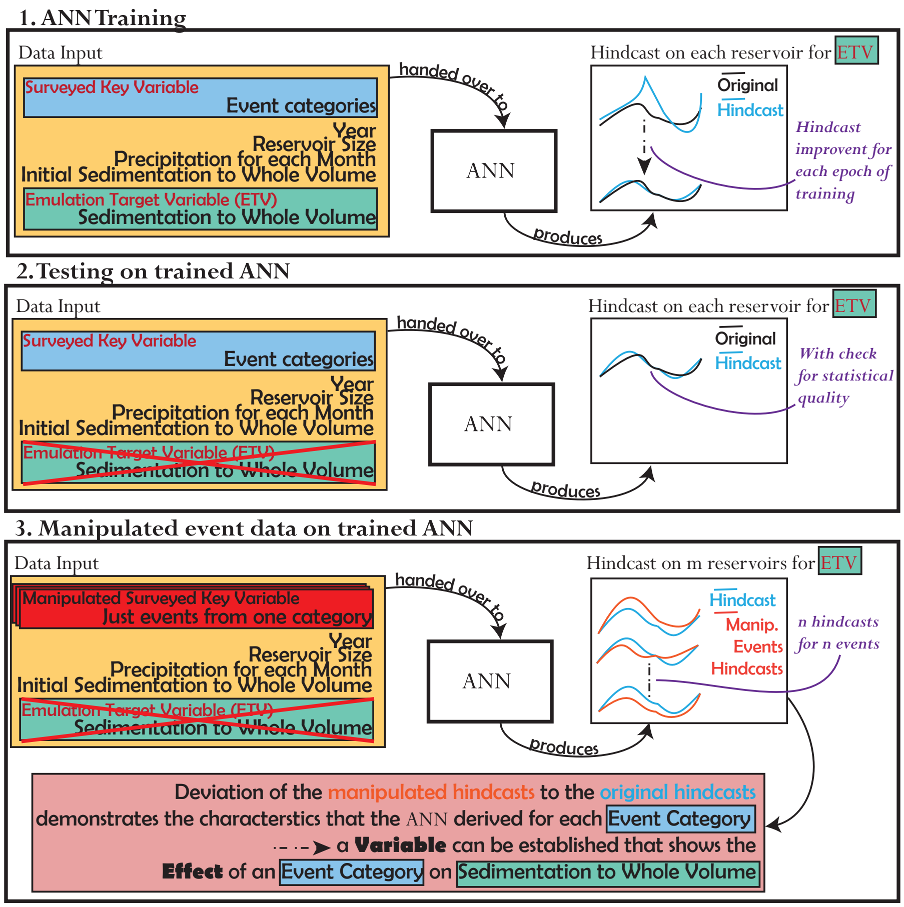

Figure 5.3: Three main steps for obtaining the desired information on the impacts of IMST and events on siltation

The process uses the following **input variables**: *event categories* (variable of which the effect is surveyed), siltation to whole volume (variable that is to be affected by the others), *reservoir size* (to roughly distinguish between substantially different reservoir types), *precipitation for each month* (to roughly distinguish between substantially different reservoir types), *year* (as a marker for a continuous time series), and *initial sedimentation to whole volume* (to enable the ANN to create a time series hindcast). The **output variable** is the: *general deviation of hindcasts that were manipulated by a sole event category from the original hindcast* (to measure the relative effect of an event category on reservoir siltation).

A wide range of methodologies were applied in the stages of the present paper to execute the outline of Figure 5.3. These included data preparation, network optimization and emulation and analysis of the results. The whole process will be explained subsequently in detail. It is illustrated in Figure 5.4.

5.2.1 Base Data

The base data correspond to 1224 reservoirs throughout Japan. The data originate from various files and formats, which were joined in a semiautomated process. Altogether, a compound of data was created, which includes the reservoir size (very small: <0.35 million m³, small: >0.35 million m³, medium: >1 million m³, large: >10 million m³; and very large: >100 million m³ total storage volume [this definition was established for Japan and is not internationally applicable]), siltated whole volume, inauguration year, average monthly precipitation for each month and, most importantly, management and event notifications of the operators. The set also includes information regarding the reservoir purpose, siltated inactive storage, siltated active storage, location, and river basin affiliation; additional information was not included in the process of the present paper to further reduce the number of data input variables (see Chapter 5.4.5).

The data format is annual and incorporates all years from 2000 to 2017 (*Heisei 12-29* - 平成12-29年)); hence, each reservoir corresponds to 18 time step time series. Stations of data origin are depicted in Figure 5.5.The data are structured in three dimensions: reservoirs, time steps, and features.

The bulk of the data were provided by the *Kokudo Koutsuu Shou* - 国土交通省 (Japanese Ministry of Land, Infrastructure, Transport and Tourism, MLIT) and the *Doboku Kenkyuu Sho* - 土木研究所 (Public Works Research Institute, PWRI). Only the average monthly precipitation data were obtained from the *Kishouchou* - 気象庁 (Japan Meteorological Agency, JMA).

Hence, the data reflect the general characteristics of Japan's reservoir landscape.

5.2.2 Artificial Neural Networks

For the obtained data, a nonlinear relation is presumed. ANNs are considered a suitable tool for analysis, pattern detection and data emulation for this type of data behaviour (Gamboa, 2017; Schmidhuber, 2014; Michelucci, 2018), especially RNNs (Elsworth and Güttel, 2020; Fu et al., 2016; Petneházi, 2019).

A well-trained ANN can emulate, forecast or even create realistic results based on limited or incomplete nonlinear data (Schmidhuber, 2014; Michelucci, 2018). This data situation is given for the Japanese (or every other country's) siltation case, as demonstrated by Landwehr et al. (2020).

An ANN processes input data in various steps via simple to complex logical and calculation operations. The ANNs are structured in layers. A single operation within that layer is called an artificial neuron. The artificial neurons are (just like the biologic originals) highly interconnected.

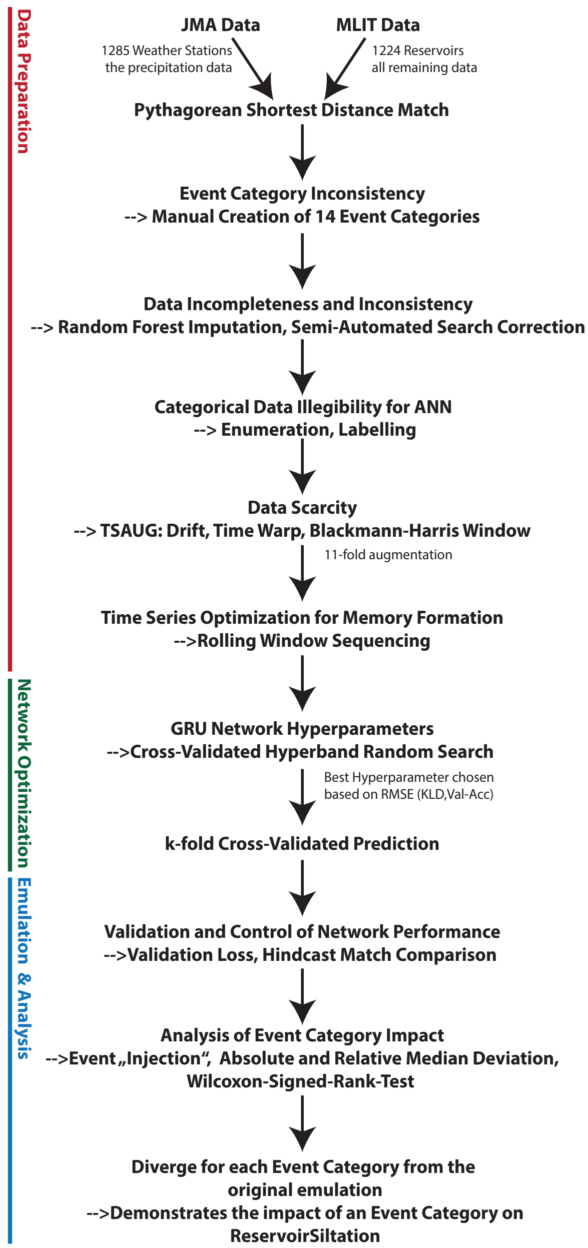

Figure 5.4: Representation of the methodological process of the present paper

In case that every cell of a layer is connected with every cell of the next layer, that layer is called *fully connected*. Each neuron consists of adaptable weights

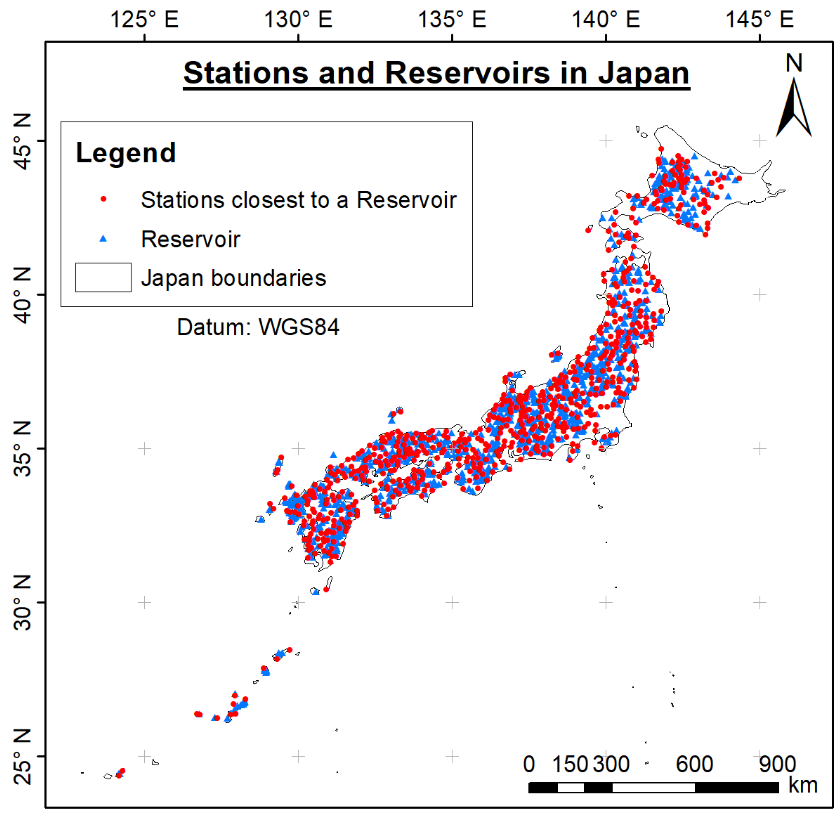

Figure 5.5: Locations of reservoirs and precipitation stations in the data set

which are the main lever for the flexibility of neural networks. An example of a simple ANN is displayed in Figure 5.6.

During a training phase, input data are processed, and the known R of the input data is provided. The result R', which is produced by the ANN, is compared to R.Their difference is called the loss. Via a loss function, all weights of the network are adapted with the objective of producing an R' that is close to R. This is called back propagation. All data are processed by the network in several iterations, the number of which is determined by the batch size. All data are refed to the network in multiple epochs, namely, multiple times. At the end of each epoch, a validation phase is conducted, in which the ANN capability is evaluated without the known result. This validation loss is a crucial measure of the progress of a network.

Afterwards, a testing phase is conducted on data that are completely unknown to the network. Again, the result R is hidden from the network. If the ANN is sufficiently flexible to create R'_{test} that is close to R_{test} is regarded as

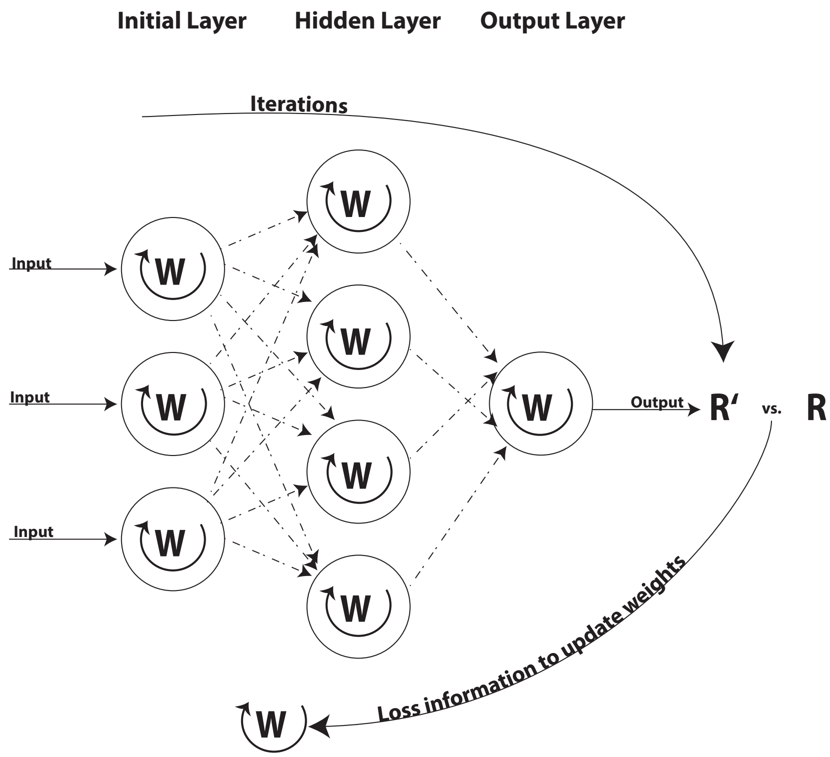

Figure 5.6: Schematic diagram of a simple neuronal network with three layers and no special neurons, such as gated recurrent units (GRUs). The ANN produces a result R' via its weighted neurons during training that is expected to mimic (with a limited variance) the known result R. The loss function is used to constantly update and improve the weights. W serves as abbreviation for all weights between the neurons.

successful, as this shows that the ANN does not merely copy the data but instead learned inherent data characteristics via the selection of suitable weights (Schmidhuber, 2014; Michelucci, 2018). As this is exactly the objective of the present study (the detection of data characteristics and extraction of their influence from a vast data set, as illustrated in Figure 5.3), ANNs are an ideal tool.

Gated Recurrent Units

For instance, GRUs are utilized to preserve information from the second word/time step of a phrase/time series that influences the fifth word/time step of another phrase/time series. Whereas basic ANNs do not provide a memory function for preserving the necessary information, basic RNNs suffer from the vanishing gradient problem, where initial weights are no longer altered and no learning occurs, thereby leading to an *incorrect* memory. The GRU structure solves this problem with the update gatekeeper function Z_t from equation 5.1 (Chung et al., 2014; Zhang et al., 2020).

$$Z_t = \sigma(X_t * W_{xz} + H_{t-1} * W_{hz} + b_z) \tag{5.1}$$

Z_t **= Update Gatekeeper Function**
X_t **= New Information Vector in Time Step t**
H_{t-1} **= Output Information from the Previous Time Step**
W = Neuronal Weight Factor
b = Bias
$_{xy}$ **= Affiliation of Bias or Direction of Weight Factor**
σ **= Sigmoid Activation Function**

It adds the new information X_t with the output H_{t-1} from the previous step. Consistent with the process of ANNs, the information is weighted by the iteratively updated weights W. The σ function scales the result to between 0 and 1. Z_t can be used as a gatekeeper that decides if and to what extent information is processed. Z_t's gatekeeper functionality is applied in equation 5.2.

$$H_t = Z_t \odot H_{t-1} + (1 - Z_t) \odot \tilde{H}_t, \tag{5.2}$$

$\tilde{H}_t$ **= Candidate Output Information**
H_t**= GRU Output Information**
$\odot$ **= Hadamard (Elementwise) Product Operator**

Z_t decides the degrees of influence of both $\tilde{H}_t$ and H_t on the output. It is also capable to turn off each one's influence completely. Thus, Z_t preserves old information when necessary or replaces or modifies it with new information from $\tilde{H}_t$. As the operation is performed elementwise via the $\odot$ operator, the gatekeeper function selectively decides to update parts of the information. $\tilde{H}_t$ is defined as follows:

$$\tilde{H}_t = tanh(X_t * W_{xh} + R_t \odot H_{t-1} W_{hh} + b_h) \tag{5.3}$$

R_t **= Relevance Gatekeeper Function**

The added new and old information is scaled between -1 and 1 via *tanh*. The information is gated via R_t which decides whether old information should influence the candidate output. R_t is displayed below and operates essentially like equation 5.1.

$$R_t = \sigma(X_t * W_{xr} + H_{t-1} * W_{hr} + b_r) \tag{5.4}$$

The complete process is illustrated in Figure 5.7. The most important step is the update gatekeeper mechanism, which enables selective propagation, updating and discarding of information.

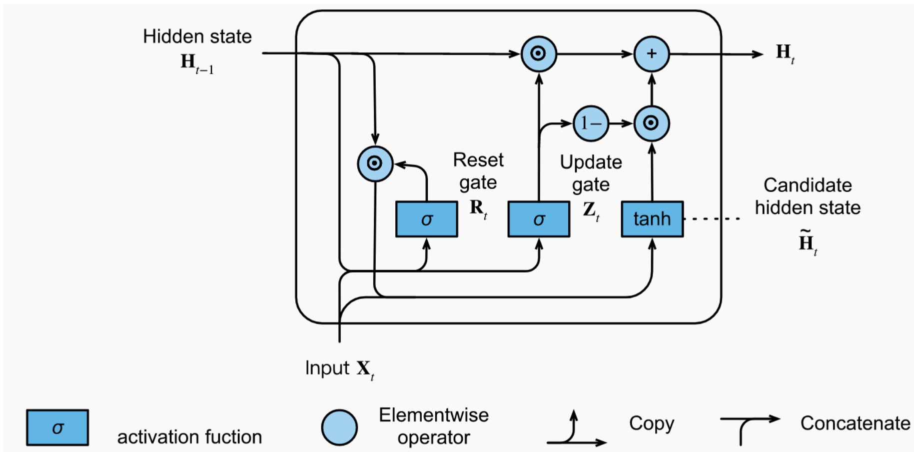

Figure 5.7: Representation of operational processes of a GRU according to Zhang et al. (2020)

This is a deciding key feature for the present study. It enables the overall network to learn and apply the characteristics of the occasionally notified event categories in training and testing. Therefore, GRUs are an ideal tool for surveying the effects of event categories and realizing the desired task frame, as illustrated in Figure 5.3.

5.2.3 Data Preparation

Precipitation measurement stations and reservoir locations were not concordant (s. Figure 5.5). The Pythagorean theorem was applied to match each reservoir with its closest precipitation station (see Figure 5.5).

The data for reservoirs and precipitation is extensive. However, not in all cases sedimentation or precipitation data was continuous, complete or accurate. This was due to gaps in measurement, typing errors of operators or the simple fact that stations or reservoirs were just inaugurated after the year 2000.

Random Forest Imputation based on Stekhoven and Bühlmann (2011) was was utilized to fill the gaps smoothly with the objective of imitating natural conditions that were derived from available data. To realize this objective, the algorithm utilizes the Gini impurity, which measures the likelihood of randomly chosen values fitting into a specified data distribution. The algorithm uses a likelihood divide that is based on the Gini impurity (it branches into two directions) and continues with branching until it reaches a level where it cannot further reduce the Gini impurity. Thus, it forms a tree. This methodology is applied various times with randomized values to create a random forest. The values with the lowest Gini impurity are chosen to fill the data gaps (Koehrsen, 2018).

For unavailable data, an out-of-bound dummy value was chosen. In the case of nonconcordance, e.g., when siltated active and inactive storage would not sum to complete siltation, semi-automated search correction (a simple Visual Basic algorithm that adjusts values and, in case of inconsistencies, leaves the final verdict to humans and, therefore, is semi-automated) was applied.

Operators of the 1224 reservoirs left notifications regarding special IMSTs and (natural) events. Those notifications were neither normed nor streamlined and were left to the respective employee's intention, interpretation and preferred Japanese syntax and semantics. Consequently, there was no unique pattern that could be interpreted by a neural network. Hence, the notifications were manually interpreted and unified into fourteen overarching categories of events and IMSTs that were most common or frequent. They are listed in Table 5.1.

Table 5.1: Event Categories from MLIT data alongside the prevailing technical terms of the Japanese original

Event Categories	イベント項目
Bypass	バイパス
Upstream Dam Installation	上流ダム設置
Unknown	不明
Flood/Taifun	出水や台風
Earthquake	地震
Sediment Relocation	堆砂移動
Dredging	屈出
New Observation/Calculation Methodology	新たな観測や計算方法
Alteration of Dam Volume/Height	貯水量の改変やダムの嵩上げ
Termination of the Reservoir	施設廃止
Spilling	放流
Drought	渇水
Measurement Error	測量誤差
Management Change	経営変化

The categorized IMSTs and events were - similar to other categorical values - labelled and enumerated, which rendered them interpretable for machine learning.

ANN performance depends on the availability of vast data input with substantial data variety to avoid overfitting (Zhang et al., 2018a; Allamy, 2014). This is also valid for time series surveys (Landwehr et al., 2020). The larger the dataset is, the higher the probability of an ANN adapting to unique data patterns and, thus, detecting the influence of the aforementioned event categories. Hence, it is necessary to artificially augment the data for two main reasons:

1. *To increase the absolute number of events with reduced appearance.*This helps the ANN detect rare events and learn from them. In the original dataset, various events are rare (or very rare); therefore, augmentation is mandatory.

2. *To increase the data variety.* Variety (e.g., event occurrence or siltation rise) helps the ANN not merely copy data patterns of the training set but

also learn its inherent information. When unknown (test) data are faced, data variety (produced by data augmentation) helps the ANN flexibly adapt.

Thus, the available data were augmented using the TSAUG (time series segmentation) algorithm based on Wen and Keyes (2019). It was selected because it enables the use of semi-intelligent augmentation techniques. The algorithm connects events to corresponding time series patterns and induces semi-randomized varieties to artificially created copies of the original time series compound.

The following techniques were used: 10-35% drift with 80% probability of occurrence (Um et al., 2017), a Blackmann-Harris-based window function with 80% probability of occurrence (Smith, 2011; Nuttall, 1981) and randomized time warping (Um et al., 2017). These techniques shifted the occurrence of events and induced a variety of slopes and patterns. Each of the original 1224 time series was augmented ten times, thereby creating a data set of 13464 reservoirs (1224 of them original) with 18 time steps.

Each reservoir's 18 time step series was sequenced with a rolling-window algorithm that was used in forward projection to provide a more effective memory function of n consecutive years s (de Meer Pardo, 2019). The rolling window always uses the last predicted value and n of its predecessors. The initial prediction is determined by the original data values. n was chosen to be 4 in the present paper, which was determined by the lower loss and higher accuracy values of the subsequent ANN.

Finally, the data were standardized via normalization and separated into randomly organized test (10% of the data), training (81% of the data) and validation (9% of the data) sets according to the requirements of the 5.2.2).

Target Value

The target value that will help retrace the effects of events or IMST on reservoir siltation must serve as a comparative value across all types and sizes of reservoirs. Thus, it must be relevant and capable of serving as reference for reservoirs that are not part of the data set, namely, the target value must form a reference class for the generation of an outside view (Kahneman, 2011; Flyvbjerg, 2016). In contrast to optimistic bias detection (the classical use case of the outside view) (Landwehr et al., 2020), the effects of IMST and events on siltation are paramount in the present paper.

Hence, a value that is based on a high variance is not recommended (such as inactive volume siltation objectives (Landwehr et al., 2020)). Rather, a stable relative value is needed. Therefore, siltation with respect to the whole reservoir volume is chosen as a comparative parameter for the formation of the desired reference class. To determine whether an event category indeed reduces or enforces siltation across a high variety of reservoirs, the impact of the event category must be detached from other key data. This is a highly complex mass data analysis process for which ANNs are suitable tools.

5.2.4 Applied GRU Network and its Hyperparameters

As described in Chapter 5.2.2 GRU layers proved to be a highly promising tool for time series prediction data characteristic detection. They are even a valid alternative to the often-used LSTM units. In various cases, GRUs yielded better results due to their less complex operational structure (Gao and Glowacka, 2016; Che et al., 2016; Wielgosz et al., 2017).

The ANN that was designed for this study consists of *bidirectional* GRU layers for preserving both past and predicted features of the LSTM. At this stage, underfitting (Allamy, 2014) and overfitting (Zhang et al., 2018a; Allamy, 2014) issues are addressed with two dropout layers (Park and Kwak, 2017). This is followed by a simple *time distributed* fully connected layer. This serves to analyse each of the GRU outputs in time series order. The output is followed by a flattening layer that reduces the dimension, which is necessary for generating the desired target value output. The network is concluded by two fully connected layers, which generate the output for the target value. The structure is illustrated in Figure 5.8. As the dropout and flattening layers do not consist of their own parameters, they are displayed in an in-between style.

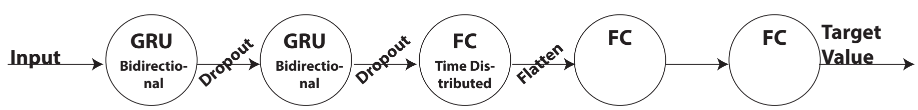

Figure 5.8: A simplified version of the developed network; FC: Fully Connected

ANNs are subject to hyperparameters that regulate them (see table 5.2. These hyperparameters have a tremendous influence on the ANN performance (Michelucci, 2018; Nisbet et al., 2017).For ANN design, setting of the hyperparameters is one of the most challenging steps (Claesen and Moor, 2015).

To select the optimal operation environment for this study, the best-performing hyperparameters were chosen using an iterative cross-validation hyperband random search process (Jiang and Chen, 2016; Li et al., 2018). In three attempts, the root mean square error (RMSE), valorization accuracy (Val-Acc) and Kullback-Leibler divergence (KLD) (Clim et al., 2018) were utilized as statistical guidance for the iterative optimization process. The promising median absolute deviation (MAD) was not used due to technical limitations (Gorard, 2013; Landwehr et al., 2020).

While the Val-Acc and KLD optimizations did produce underfitted and, thus, not useful results, RMSE optimization produced hyperparameters that led to a promising low validation loss and, hence, a satisfactory fit for R' (see Chapter 5.2.2). The obtained hyperparameter values are listed in Table 5.2. They led to a network with 4,148,271 trainable values that were expected to be capable of deriving the desired information according to Figure 5.3.

Table 5.2: Overview of cross-validated hyperband random searched hyperparameters. Abbreviations: *ReLU - Rectified Linear Unit (Nwankpa et al., 2018)*, *Nadam - Nesterov-accelerated Adaptive Moment Estimation (Ruder, 2017)*, *MSE - Mean Square Error*

Hyperparameter	
1st GRU-layer size	542
2nd GRU-layer size	242
Time-Distributed-layer size	242
Fully-Connected-layer size	100
1st GRU-layer activation	ReLU
2nd GRU-layer activation	ReLU
Time-Distributed-layer activation	ReLU
Fully-Connected-layer activation	ReLU
1st Dropout-layer percentage	0.45
2nd Dropout-layer percentage	0.35
Optimizer	Nadam
Learning Rate	0.000443
Loss	MSE
Batch size	242
Epochs	61

5.2.5 Metrics for GRU and result performance

The validation loss was selected as a metric for evaluating the training optimization. The ANN uses a loss function to measure and subsequently reduce the difference between the produced prediction and the already known results (Wang et al., 2018) as indicated in Chapter 5.2.2. The validation loss is calculated from the separated 9% of the data, which is provided to the network in each iteration. The lower the validation loss is, the better the network adapts to unknown data such as the test data. A perfect 0-loss match is, however, undesirable, as it would indicate overfitting on the validation data set (Zhang et al., 2018a; Allamy, 2014), thereby demonstrating that the internal training data variance is likely not sufficient for the creation of a highly adaptive network.

Hindcast emulations for each original or artificially produced reservoir data item of the test set are expected as results. With the hindcast approach, known data are treated as new data for the prediction of future data - with the real result used as a measure for control. In the case of a satisfactory match between the emulation and the original data, the general capability of emulating completely unknown data or completing forecasting tasks is demonstrated. Alongside the validation loss, the hindcast match comparison evaluates the general functionality of the trained neural network.

To examine the effects of the event categories, a semi-randomly selected variance of the original reservoir data was modified and retested. The only criteria were that selected decades of reservoir erection and all volume sizes of reservoirs were included in each possible combination within the selection; therefore, it was semirandom.

The data modification was restricted solely to the event categories. For each reservoir, the original event annotations were deleted, and an "injection" of each event from the fourteen event categories was undertaken for the period between 2007 and 2011. The neural network, which was trained on the original training data, subsequently executed an emulation for each of the modified reservoir data sets, namely, 15 (14 categories plus the original data) times 19 (five size categories times four selected decades minus one nonexistent combination) emulations were conducted. The process is illustrated in Figure 5.9.

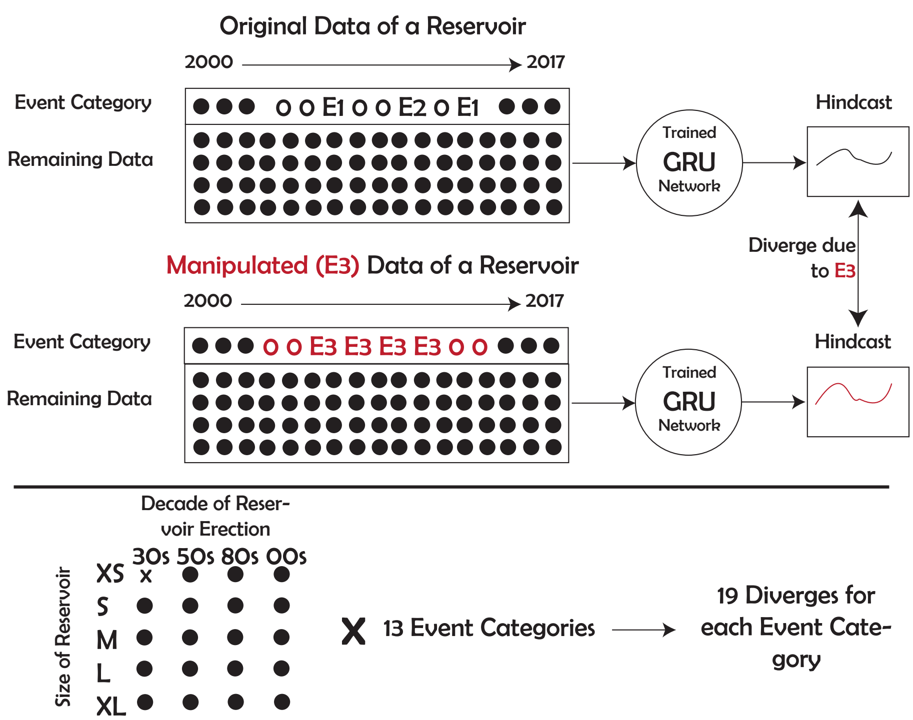

Figure 5.9: Manipulation of the event categories causes the trained network to produce different hindcasts. The difference reflects the impact on siltation that the trained network has learned for the corresponding effect.

The results were compared to the original data via a simple absolute median of the deviations. The median was selected because it reduces –in contrast to the average –the influence of outlier values on the statistical outcome.

Each of the event categories represents a unique distribution across the reservoirs. As the modified and original emulation data distributions reflect connected but not normally distributed data distributions, a Wilcoxon signed-rank test was conducted (Wilcoxon, 1945) between the original distributions and those for each event category.

In case of significance, the null hypothesis that the modified and original data are of the same distribution, namely, that the event categories have no effect, would be rejected. The simple average would reflect the relative impact of each event category compared to the original distribution. This would imply that the neural network could actively derive and learn from the data whether each event category has an individual effect. Thus, interference by other side effects (other data) could be excluded. This concludes the methodological process of the present paper, as illustrated in Figure 5.4.

5.3 Results

The data categories that were used for the training and testing of the network were event categories, reservoir size, precipitation for each month, year, and initial sedimentation to the whole volume.

Variations (e.g., for batch-size or epochs) of the hyperparameter optimal values from Chapter 5.2.4 were evaluated to obtain a better validation loss result. Nevertheless, the originally produced hyperband random-searched values proved to produce one of the best results with a validation loss of 0.3724 after 61 epochs. Better results from other configurations were insignificantly better, which is why the hyperband-optimized configuration was chosen for further analysis.

The network is designed to produce fifteen emulations for each reservoir, namely, fifteen hindcasts. With each new reservoir from the data, the network starts a new fifteen-step emulation turn. To display them more clearly, the emulations were structured linearly one after each other in Figure 5.10.

A hindcast match comparison and the validation loss demonstrated that the GRU network can predict convincingly on completely unknown reservoirs with extremely different configurations. It has learned to derive complex information from an extremely reduced essential data pool.

The subsequent objective was to disentangle the information and identify the influence of the network that was learned from the data for the event categories. This was conducted according to Chapter 5.2 and Figure 5.3. Examples of the randomly selected reservoir cases and the respective influence of the event injection are presented in Figure 5.11.

The effects of event category "injections" differ in terms of both extent and shape among the types of reservoirs. According to Chapter 5.2.5 and Figure 5.9, the event manipulation was established between 2007 and 2011. In concordance, no deviation effects from the original hindcast are visible before time step four in Figure 5.11. However, the influence of events continues to affect the hindcast for almost all subsequent time steps.

The effects are identified using the simple absolute median of the deviation from the original data, as described in Chapter 5.2.5. rejected for all of them

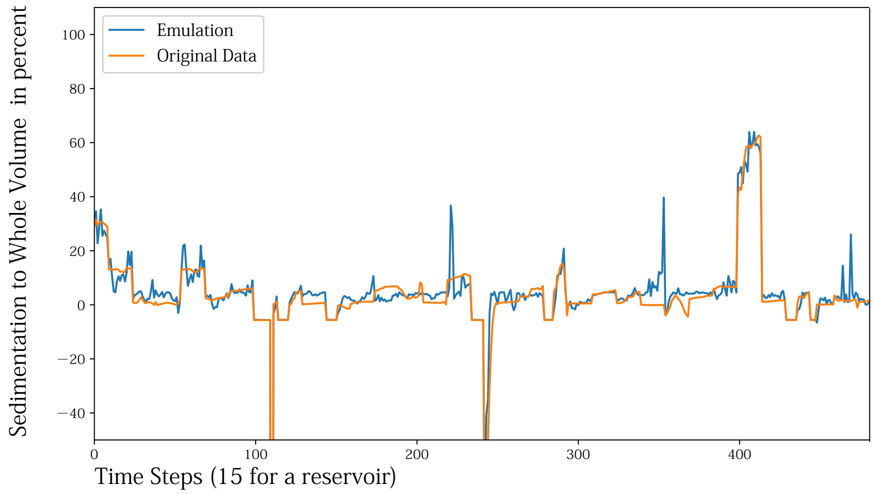

Figure 5.10: Emulations of sedimentation to whole volume for 32 reservoirs in a randomized order. Every 15 time steps a new reservoir is represented.

with (most often) very high confidence, as the Z-values ranged far outside the quantile values (+/-1.96 for 95% confidence).

Table 5.3 presents the effect that the GRU network has learned from the data for each event category with the methodology that is described in Chapter 5.2.5. The lower the absolute median deviation is, the larger the reduction in siltation per whole volume. The values are specified as percentages in comparison to the original assigned event categories. For example, in the case of *dredging*,the median for the 19 emulation cases was 0.316% lower than the original hindcast of the GRU emulation. For reservoirs like the ones of the *Tsuruta Dam* (鶴田ダム) or the *Honna Dam* (本名ダム) from Figure 5.2, which both had roughly 8.000-9.000 thousand m³ of sedimentation in 2017, this would mean 25.000 m³ less sediment - which is roughly the plenary hall of the German Bundestag (Albers, 1999). Thus, the median reduction via *dredging* is considerable.

The key message of Table 5.3 does, however, not reside within their absolute values but in the relation of the values to each other. Hence, according to the GRU network, *Dredging* has a 29% higher impact on the reduction in siltation per whole volume than *spilling* (see column RM of table 5.3).

5.4 Discussion

The results provide compelling insight into the sedimentation management effect, as this is - to the best of the authors'knowledge - one of the few, if not the only, mass data studies of siltation. However, the results are not entirely intuitive and, thus, are subject to discussion. In addition, the ANNs and the

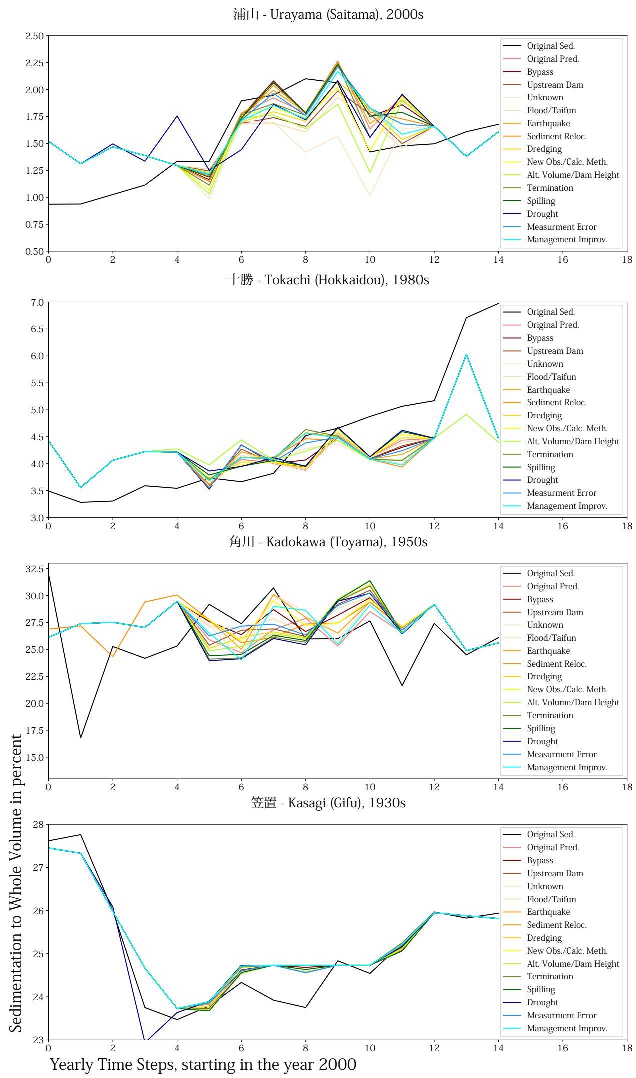

Figure 5.11: Examples of the randomly selected reservoir cases: Comparison of the originals with the fourteen event category injections

data input are worth to discussed in order to better understand the current and optimize future research.

5.4.1 Event Categories

Table 5.3 presents the efficiency the GRU network for each event category. Before debating the implications of the results for various categories, it is important

Table 5.3: Deviations among the semirandomly selected and event-manipulated reservoirs. Abbreviations: *AMD - Absolute Median Deviation for Sedimentation to Whole Volume in percent*; *RM - Relative Median, i.e. ranking of the lowest AMD (100%) compared to the highest AMD (0%)*; *Wilcoxon-Z-Value - Approximation for critical values of the Wilcoxon-Signed-Rank-Test to the normal deviation for n>20 test values (Gibbons and Chakraborti, 2011)*

AMD	RM	Event Category	Wilcoxon-Z-Value
-0.31613	100.00000	Dredging	-5.68605
-0.30385	96.70048	Measurement Error	-10.73597
-0.21024	71.54733	Spilling	-1.75157
-0.20797	70.93692	Sediment Relocation	-8.60382
-0.14126	53.01029	Alteration of Dam Volume/Height	-5.19799
-0.13491	51.30526	Bypass	-6.58629
-0.13016	50.02848	Flood/Typhoon	-1.92266
-0.07428	35.01180	Upstream Dam Installation	-2.99249
-0.06804	33.33494	Management Change	-5.92457
-0.02223	21.02507	Unknown	-1.94327
-0.01540	19.19086	Drought	-3.54715
-0.00069	15.23878	Termination of the Reservoir	-2.16655
0.02835	7.43600	New Observation/Calculation method	-1.89072
0.05602	0.00000	Eearthquake	-1.94858

to closely examine the underlying data of the events.

Interpretation conflicts

The events are not a homogeneous mass. The MLIT received the event annotations from the operators.

The MLIT has improved the format and standardization of siltation data over the years. The event annotations, however, are only vaguely standardized.

This has the advantage that operators can individually describe the highly diverse characteristics of reservoirs and events within Japan. However, the substantial variance of the descriptions from the operators often leaves excessive room for interpretation.

For example, the 2010 event notification 葦繁茂によりダム内への土砂流入をせき止めた - *Reed growth prevented sediment from flowing into the dam* of the *Amagime* (天君) reservoir in the Kumamoto Prefecture is the source of the following interpretation problems:

1. The notification could be incorporated into a larger category, namely, *Landscape Management*. Landscape management for sediment entry reduction is a hot topic for reservoirs (Kondolf et al., 2014; Sumi and Kantoush, 2011). However, it is unclear whether other operators mention landscape management practices when they carry them out. In fact, the event notifications regarding landscape management were scant for the

whole data set. It can thus be doubted that every landscape management practice was notified.

2. The reaction to the notification remained unclear. Was the reed cut? Was more reed planted? Certainly, there was a reaction, but its nature remains unknown.

In the end, the Amagime notification was included into the category *Management Change*. This is correct, as a management change was made. Nevertheless, as the true nature of the change is unclear, the probability that the effect of the Amagime measure conflicts with other entries of the *Management Change* event category is high. This might explain the modest effect that the GRU network derived for the *Management Change* category. *Management Change* might be much more efficient than indicated by the present paper, but event interpretation conflicts cause internal ambiguity.

Those types of interpretation conflicts did not prevail for the data set, but they were also not rare among the 1224x18=22032 possible event entries. Thus, the event categories are not free from impurities. The event reporting and its implications could be better, but the MLIT data in their current form already provide unique and valuable piece information.

5.4.2 Restricted Occurrence

Various events suffered from significant application restrictions. A paramount example of this is the category *bypass*, which only has two occurrences within the data set. A *bypass* is presumed to be a highly impactful sediment management strategy (Boes et al., 2014; Auel, 2018). However, it is subject to tremendous application costs due to its complex construction characteristics (Morris, 2020). This limits the application of this strategy drastically, as the data set demonstrates.

Due to the uniqueness and promising outlook of the technology for future applications (Morris, 2020), it was decided to keep the *bypass* as a highly unique event category. The limitation effect was reduced by the application of the TSAUG methodology (Chapter 5.2.3). Disproportionate augmentation of the bypass cases was also considered, but it was decided that the base data restriction would contort the actual results too severely in this case. Nevertheless, it is clear that the base data restriction influenced the interpretation of the GRU network. Thus, the AMD and RM values are highly indicative for the *bypass* class.

The *bypass* case is an extreme example. Most of the other categories are founded on substantially more base data (several dozen to hundreds of event entries).

5.4.3 Spilling, Sluicing, Floods and Typhoons

Spilling (流出-Ryuushutsu)), which is also referred to as flushing, is among the most common sediment management techniques (Kantoush and Sumi, 2017;

Morris, 2020). It is conducted by elevating the hydraulic scour. Although the definitions partially overlap, it should not be confused with sluicing, which typically involves the utilization of naturally occurring floods.

Interestingly, *Spilling* is considered to have substantially less impact than dredging, which is also often applied and which the GRU network found to be most efficient in sediment reduction.

Sluicing, in contrast, was not assigned its own category. This is due to two reasons:

1. It is sometimes treated homologously to *Spilling* by operators
2. Flood events are used for sluicing, but depending on the type and fierceness of the flood (or typhoon) and the type of reservoir, sediment reduction or successful application of the sluicing technique is not always guaranteed. Thus, after flood event notifications, a sediment rise or decrease is observed within the data set. Nevertheless, it is impossible to distinguish flood events with sluicing from those without sluicing, as the information that is provided by the operator is restricted.

Therefore, the category was named Flood/Typhoon. Its data are not completely consistent. Nevertheless, it insinuates that Japanese operators are prepared to use (extreme) flood/typhoon events for sluicing since the overall GRU result demonstrates a reduction in sedimentation to the whole volume due to floods/typhoons.

5.4.4 Measurement Errors, Sediment Relocations and New Observation/Calculation Methods

Events need not always be intended or be of vis major. Frequent errors or unforeseen developments due to technological improvement impact sediment statistics. Three event categories are exemplary:

1. *Measurement Error*. This is one of the most frequently occurring event entries. Hence, even in highly organized countries such as Japan, absolute certainty regarding data is not guaranteed. Moreover, it demonstrates that Japanese authorities and operators are willing to admit errors so that correct data can be obtained and higher operational sustainability realized. Interestingly, new measurements frequently insinuate overestimation errors in prior measurements.
2. *Sediment Relocation*. Notification of this event was frequent. This is assumed to be due to the occurrence of floods/typhoons or the use of new observation/calculation methods. Additionally, it is possible that 堆砂移動-*Sediment Relocation* is used as a filler declaration when the real reasons are unknown.
3. *New Observation/Calculation Methods* This event occurs frequently when advancing to more sophisticated bathymetric techniques (Balan et al.,

2013; Kantoush and Sumi, 2017; Adebayo Olubukola et al., 2020).Measured values can significantly deviate from previous values.

5.4.5 Data Input

The data were gathered under the objective of universal applicability: The objective was to obtain a result of high significance without the necessity of assembling data that are not available in many countries due to restrictive governance structures (Pahl-Wostl, 2015). Thus, more accurate results are likely to be obtained with more data input.

However, the present paper demonstrates that highly promising results can already be produced with only a handful of influential factors.

The exact relation between most of the data and event categories remains a subject for further investigation (e.g., whether there is a satisfactory correlation between flood/typhoon events and the precipitation data and its impact on sedimentation).

5.4.6 Networks

There are many approaches that might lead to advanced ANNs that can yield more accurate results. LSTM layers are a possible alternative for GRU layers, and convolution and average pooling layers are also interesting approaches for information extraction (Tang et al., 2020). The same might be true for a more extensive use of time distribution layers.

Another opportunity to generate more realistic artificial data is assumed to lie within the use of generative adversarial networks, which have already produced convincing results for artificial image generation (Islam and Zhang, 2020; Han et al., 2019).

The ANN opportunities are vast and were partially evaluated in this study. The eventually utilized GRU network proved to be the most reliable network that yielded the best results with the resources that were available at the time of the study.

5.5 Conclusions and Outlook

The presented methodology has high potential for scenario testing of management strategies. The impacts of highly complex technologies on sedimentation comportment can be tested with moderate effort and data demand to realize hindcasts with satisfactory performance. The foundation on real data corresponds to the outside view and reference class that are demanded by Kahneman (2011); Flyvbjerg (2016) for grand infrastructures.

Reservoirs are objects of high variance for multiple reasons, which range from climate and purpose to technology. Consequently, the individual characteristics of reservoirs play a key role in classical sediment development analysis. However, the ANN methodology enables both the derivation of conclusions from the big general picture of several hundred to thousand reservoirs and attribution to individual factors. This is the main advantage of the presented methodology. Nonetheless, it cannot replace highly detailed individual reservoir analysis. The ANN methodology is a useful supplement.

In the special case of Japan, continuation and enhancement of the data set are paramount. More details for the event categories might be revealed if operators are approached directly (however, this is connected with a very a high work load).

The potential power that governmental approaches possess is emphasized. Governmental and management structures and decisions may strongly influence sediment accumulation and, thus, the longevity of reservoirs. They incorporate the smart design and application of sediment technological countermeasures, such as spilling, dredging, sluicing or bypassing, that the results demonstrate to be efficient. They also incorporate adaptive measures, such as the modernization and realization of observation and control (measurement errors and new observation/calculation methods) and the formation of new management structures (management change). Overall, the results demonstrate that technological progress cannot exert its full effect if it is not supported and distributed by overarching governmental and management structures.

Further investigation of the data set with other approaches is necessary. Additional data classes are likely to provide further insight into various research questions, e.g., with respect to landscape management. Upcoming multivariate, multi-time series approaches with various ANN methodologies will produce even more detailed findings. Especially the presumed opportunities of General Adversarial Networks (GAN) to mimic naturally existing data sets are emphasized. A breakthrough GAN research regarding data structures would facilitate data enhancement in a supposedly more natural manner.

Since the proposed approach is based on a reduced variety of data input, global applicability is assumed. Countries with scant data availability can benefit from either the methodology or pretrained networks.

5.6 Acknowledgements

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5.7 Declaration of Originality

I declare that this research is my own work except where there is clear acknowledgement and reference to the work of others. This research does not contain material that has already been used to any substantial extent for a comparable purpose.

CHAPTER

6

WATER MANAGEMENT CAUSES INCREMENT OF RESERVOIR SILTING AND REDUCTION OF WATER YIELD IN THE SEMIARID STATE OF CEARÁ, BRAZIL

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Abstract

The semiarid State of Ceará, Brazil, implemented its water management system in the early 1990s. The drought-prone State is densely populated and its supply strongly relies on surface reservoirs, whose yield reduces with silting. Using artificial neural networks and data from 141 monitored dams, we show that the silting ratio of the reservoirs significantly enhanced after the implementation of the water management system. An explanation for this fact is that, since the management started, water withdrawal increased, leading to lower reservoir levels at the beginning of the rainy season. This reduces the probability of spilling, which is the main mechanism of sediment outflow, thus causing excessive siltation. As a result, water availability is expected to reduce by 6% in 30 years, creating a clear contradiction with the management objectives. To tackle this problem, four actions are recommended: to include spilling in the operational rules, to reduce erosion in the basins, to execute sediment reuse policy, and to implement water-demand management.

6.1 Introduction

Scarcity of water is one of the main problems of dryland societies (Sharafatmandrad and Mashizi, 2020). The Brazilian state of Ceará, located in the Caatinga Biome, semiarid region of the Country, has suffered the consequences of water scarcity for many centuries (Gaiser et al., 2003), mostly due to the intermittence of its rivers associated with long lasting droughts and high demand (Aragão Araújo, 1990). As a result, in the end of the XIX Century, the federal government started the so-called *hydraulic policy*, which consisted of building dams and the associated infrastructure to store the water surplus of the wet months to dispose of it in the dry season (Medeiros and Sivapalan, 2020). The first striking action of this policy was the construction of the Cedro Dam (126 hm^3) between 1878 and 1906. The monotonic approach of dam building prevailed until the late 1980s, when a new water policy was established (Campos, 2015). The State installed a novel institutional framework to tackle the water issue in 1987; in 1991 the first water resources plan was published; in 1992 the new State water law was enacted; in 1993 the Water Resources Company (COGERH, which acts as the water agency) was created; and in 1994 the first river basin committee was installed. Because of their relevance to the water supply in Ceará (Aragão Araújo, 1990; Krol et al., 2011; Alves et al., 2012; Peter et al., 2014; Campos, 2015), surface reservoirs remain central to the management approach.

In Brazil, the water-management era boosted in the early 1990's, shortly after the implementation of the Country 1988 democratic constitution (Keck and Abers, 2004; Campos, 2015). The national policy was formally established when the new federal water legislation was enacted in 1997, five years after the approval of the Ceará State law. The new legislation improved considerably in comparison with the former (from 1934), whose main focus was the generation of hydro-power. Among the legal advances, there are the assertions that the water is a public good; that it must benefit multiple uses; that water quality must be ensured; and that the decision-making process must be participatory by means of democratically-elected river basin committees. Despite the merits of the new system, several concerns have been raised, such as the prevailing influence of powerful corporations to the detriment of less influential societal sectors (Broad et al., 2007; Moraes and Perkins, 2007; Taddei, 2011; Libanio, 2018; Salinas et al., 2019; Miranda and Reynard, 2020).

The question raised hereafter is whether the implementation of the water management could have notably changed the water balance and, thus, the sediment redistribution pattern in the basins. In fact, de Araujo et al. (2006) showed how surface-reservoir siltation causes depletion of the water yield with time, which is a serious drawback for semiarid regions. Our key concern is that eventual changes caused by the new management practices may reduce the water availability with time, generating a serious contradiction. The objective of this work was, then, to verify, based on data from 141 monitored dams in Ceará, if the siltation pattern changed after the implementation of the water-management system (1992/1993) and, if confirmed, to which extent these changes would bounce back to the water availability.

6.2 Methodology

6.2.1 Study area

The study area is the Brazilian semiarid State of Ceará. With a surface of 148,000 km^2 and 9.1 million inhabitants, Ceará has a critical water deficit to the atmosphere: the average precipitation is below 800 mm.yr^{-1}, whereas its potential evaporation surpasses 2,000 mm.yr^{-1}. Besides, more than 85% of its territory is located on top of the crystalline basement, where rivers are intermittent and groundwater is scarce and frequently salty (Gaiser et al., 2003; de Figueiredo et al., 2016). Additionally, the Brazilian semiarid region is often affected by droughts (Marengo et al., 2017; Medeiros and Sivapalan, 2020) that may last several years (de Araújo and Bronstert, 2016; Marengo et al., 2018a). Due to the dry spells and to the high demand, water disputes have frequently disrupted conflicts (Aragão Araújo, 1990; Taddei, 2011). In order to solve this problem, decision makers built a dense, complex network of on-river reservoirs that supplies approximately 90% of the State water demand (Mamede et al., 2012). According to Peter et al. (2014), there are tens of thousands of dams in the State of Ceará, built continuously during one hundred years (mostly from 1910 to 2010), whose sizes range from micro (10^{-2} hm^3) to very large (10^4 hm^3). This complex network reduces the system vulnerability towards hydrological extremes, both droughts and floods (Peter et al., 2014). It also impacts the system water availability (Krol et al., 2011; Malveira et al., 2012), energy balance (Nascimento et al., 2019), and sediment redistribution pattern (Lima Neto et al., 2011; de Araújo et al., 2017).

What concerns sediment dynamics in Ceará, de Araújo et al. (2017) gathered measurements from 26 sites of the Jaguaribe River Basin (75,000 km^2), the largest in the State. The sites, which have different catchment areas (10^{-4} - 10^{+4} km^2) and various monitoring techniques, show that sediment yield in the basin ranges from 10^0 to 10^3 Mg.km^{-2}.yr^{-1}. The authors identify the catchment area, the presence of numerous small dams upstream, and the basin geology as the key factors influencing sediment yield in the Jaguaribe Basin. Lima Neto et al. (2011), who assessed SY in the Upper Jaguaribe Basin (24,600 km^2) based on data from 25 years, concluded that the retention caused by the dense network of small and middle-sized reservoirs is considerable, trapping almost 60% of the whole basin sediment yield. Farias et al. (2019) showed that unpaved rural roads, which contribute to 16% of SY in the Upper Jaguaribe Basin, are a factor that should be regarded when managing sediment in Ceará, considering its long rural-road network. Besides, Oliveira et al. (2016) have found evidences of organochlorine pesticides in the sediments of the Jaguaribe River, which also threatens its water availability.

6.2.2 Reservoir's morphological data

We selected 141 monitored dams in Ceará (Figure 6.1 and Table 6.1), among which the one hundred largest ones in the State. All selected reservoirs dispose of morphological data both in the construction and in a control year. The control surveys consisted on the reservoir bathymetry, undertaken after the implementation of the new State water policy by the management company (COGERH), except for the Marengo (Zhang et al., 2016b) and the Aiuaba (de Figueiredo et al., 2016) dams, which are monitored by the HIDROSED Research Group. The bathymetric surveys used the accurate methodology explained in detail by Lopes and de Araújo (2019). It is relevant to stress that, although the selected cluster represents only 0.5% of the existing dams in the State (Mamede et al., 2012), its storage capacity encompasses almost 15 km^3 (85% of the State capacity), whereas its yield with 90% annual reliability Q_{90} adds to 4.5 km^3.yr^{-1}, or 89% of the State surface-water availability.

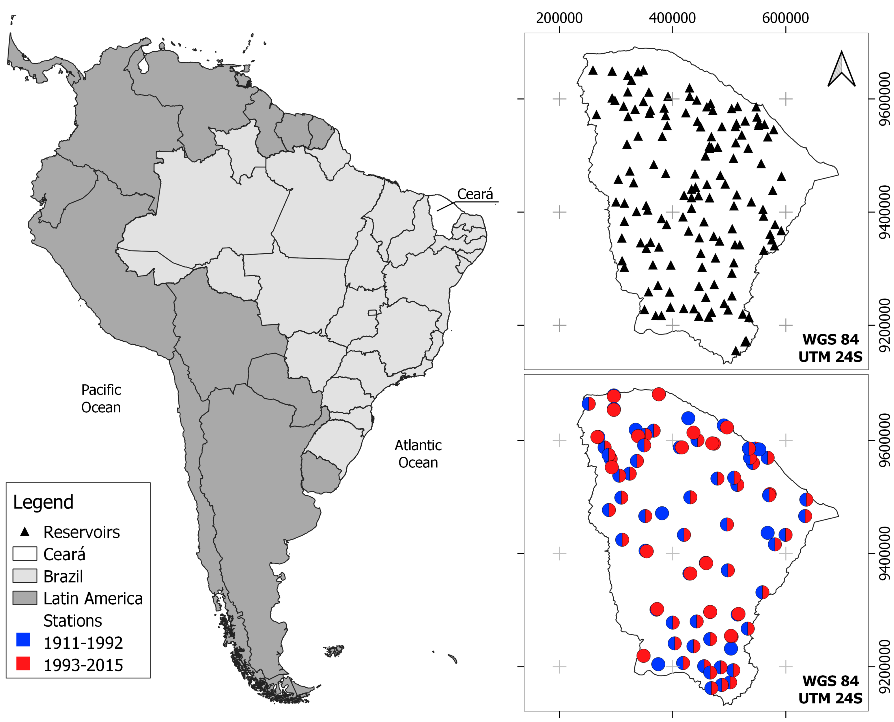

Figure 6.1: Location of Study area, reservoirs and rainfall gauging stations. In colour we indicate the time periods of usage of each station.

		Construction			Bathymetry				
Ranking	Reservoir	Year	SC (hm^3)	α (-)	Year	SC (hm^3)	α (-)	Decadal silting rate	Kα
1	Castanhao	2002	6,700	34,339	2012	5,738	36,442	0.144	0.355
4	Araras	1958	980	21,005	2014	860	22,659	0.023	0.541
8	Pentecoste	1957	396	32,517	2009	360	41,483	0.018	2.461
17	Aracoiaba	2003	162	6,310	2015	154	6,743	0.043	1.220
33	Lima Campos	1924	66	24,192	2016	62	31,746	0.007	3.848
41	Varzea Boi	1954	52	15,381	2010	47	17,258	0.016	1.198
52	Malcozinhado	2003	37	10,830	2015	33	12,778	0.072	1.776
93	Varzea Volta	1919	13	12,500	2000	11	23,180	0.016	4.529
111	Bonito	1964	6.0	6,000	2013	5.6	7,736	0.015	3.407
141	Aiuaba	1934	0.062	561	2009	0.059	652	0.006	3.535
Average (n = 141)		1973	138	9,211	2013	124	10,710	0.027	1.890
St dev (n = 141)		29	611	10,787	3	530	12,144	0.036	1.423
CV (n = 141)		0.015	4.43	1.17	0.001	4.29	1.13	1.33	0.75
Minimum (n = 141)		1900	0.062	134	2000	0.059	145	0.002	0.003
Maximum (n = 141)		2013	6,700	65,070	2019	5,738	66,505	0.566	4.914

Table 6.1: Data from the 141 investigated reservoirs in Ceará both in construction and in bathymetry years (measured storage capacity (SC) and morphological parameter (α)), as well as decadal silting rate (r) and the morpho-dynamical parameter (K_α). The upper part of the table shows specific results for ten selected reservoirs, whereas the lower part shows the main statistical parameters.

6.2.3 ANN test of hypothesis

The hypothesis that water management changed reservoir siltation (see Table 6.1) was tested using Artificial Neural Networks (ANNs, see also Meshram et al. (2020)) to derive the siltation pattern for the reservoirs of Ceará. We assume that the collected data forms a representation of continued reservoir management in Ceará, i.e., a generalized time series. Key water governance events, like the new State Water Law in 1992 or the establishment of the Water Resources Company in 1993 (see Chapter **??**) and their subsequent management decisions, are assumed to impact the time series of water and sediment budgets. As the nature and effect of governance decisions are non-linear, its impact - and thus our hypothesis - on the time series data is non-linear, as well. ANNs are supreme tools to detect such kind of comportment within complex data (**??**).

Four ANNs (Long Short-Term Memory (LSTM), Feedforward Neural Network (FFNN), Multilayer Perceptron (MLP), Support Vector Machines for Regression (SVR)) were utilized based on tensorflow, scikit-learn and keras libraries to learn from the collected data (with focus on inauguration year and siltation per decade) in two 60-fold data augmentation configurations (jitter (pure Gaussian noise) and warp (Gaussian noise on Bezier-Curves)(Um et al., 2017; Le Guennec et al., 2016; Xiao and Xu, 2012)) to guarantee that results were independent of the ANN methodology. Other techniques were utilized to optimize the respective ANNs performance, among them synthetic minority oversampling technique (SMOTE) (Fernández et al., 2018) and an iterative k-fold cross-validation grid search process, based on median absolute deviation (MAD) (Gorard, 2013) for optimized ANN hyperparameters (Jiang and Chen,

Table 6.2: K-fold cross-validated grid searched hyperparameters of the respective networks

Hyperparemter	SVR	FFNN	LSTM	MLP
Learning Rate	-	0.01	0.008	0.003
Batch Size	-	128	200	32
Optimizer	-	Adam	Nadam	Adam
Loss Function	-	logcosh	logcosh	-
Activtion	-	ReLU	ReLU	tanh
Epochs	-	5	12	automatic
Dropout	-	0.1	0.1	-
Hidden laye setup	-	700/150/25/50/1	1000/200/16/1	100/50/1
k-fold emulation	-	6	4	4
C	60	-	-	-
Gamma	3	-	-	-
Epsilon	0.004	-	-	-
Kernel	rbf	-	-	-

2016). The chosen hyperparameters for each network are displayed in Figure 6.2.

The networks are trained via k-fold cross validation, i.e., they are trained on k-1 parts of the augmented data set and blind-tested on the remaining k-part. In the training phase, the network interactively tries to generate emulations that explain the decadal sedimentation comportment of the received data, by reducing the error between the own emulation and the known training data result via the loss function (Schmidhuber, 2014; Michelucci, 2018). The final test on unknown test data demonstrates the network's capability to generalize on data and not to merely copy (i.e., overfit) known behavior from the training data.

6.2.4 Oversiltation impact on water yield

To assess the impact of oversiltation on water yield, we simulate two scenarios. Scenario 1 assumes the siltation rate as observed before the implementation of the management practices in 1993; whereas scenario 2 considers the siltation rate as observed after the practices. The temporal horizon of both scenarios is 30 years, starting in the bathymetry year for each individual reservoir. The VYELAS model (de Araujo et al., 2006), which is used to compute the water yield, simulates the water balance in the reservoirs using a Monte Carlos synthetically-generated inflow series and mimics operation rules commonly practiced in the State of Ceará (see, e.g., de Araujo et al. (2006)). The model demands data of seasonal water inflow (average and standard deviation), precipitation, evaporation, storage capacity (SC), alert volume, and the morphological parameter α (Equation 6.1, where y_{max} is the water maximum depth: Campos (2010)).

$$SC = \alpha . y_{max}^3 \tag{6.1}$$

Equation 6.2 represents the temporal evolution of the storage capacity as a function of the siltation rate (r, see Table 6.1), which was estimated based on data from the inauguration and bathymetry years for each individual reservoir. The index 0 refers to the initial year of analysis. Equation 6.3 also depicts how SC varies with time (t), but as a function of the rainfall erosivity (R, given in $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$) and of the siltation parameter (ξ). Due to the scarcity of sub-daily rainfall measurements in the XX. Century in Ceará, we use Equation 6.4 (Lombardi Neto and Moldenhauer (1992), validated by de Araujo et al. (2006) in the State), in which H(t) is the total monthly rainfall (mm) and $\bar{H}$ is the average annual rainfall (mm). A total of ninety rainfall stations (Figure 6.1) with consistent monitoring were selected to assess the erosivity in Ceará (FUNCEME, 2020). All stations monitor daily precipitation using *Ville de Paris* gauges and were tested for consistency and missing values. From the set of selected stations, two subset were formed: the first has sixty-nine stations with more than thirty complete years (with no missing data in the rainy season) from 1911 to 1992. The second subset has seventy-three stations with more than fifteen complete years to assess erosivity from 1993 to 2016. For each reservoir, the rainfall erosivity is taken from the closest rain gauge.

$$SC(t) = SC_0.(1-r)^{\Delta t} \tag{6.2}$$

$$SC(t) = SC_0.\left[1 - \xi.\sum_{t=1}^{\Delta t} R(t)\right]^{-1} \tag{6.3}$$

$$R(t) = 68.73.\sum_{i=1}^{12}\left[H(i,t)^2/\bar{H}\right]^{0.841} \tag{6.4}$$

In order to estimate the value of the siltation parameter in the recent period (ξ_{rec}), i.e., after the management practices implementation, we apply Equation 6.3 to the 40 reservoirs that have been constructed since 1993. This yields average ξ_{rec} = 1.13 10^{-6} $MJ^{-1}.ha.mm^{-1}.h.yr$. Then, for each reservoir built before 1993, Equation 6.5 is applied to estimate its respective parameter ξ_{old}. The average siltation parameter of the pre-1993 period ($\bar{\xi_{old}}$) equals 7.88 10^{-7} $MJ^{-1}.ha.mm^{-1}.h.yr$. The changes in the reservoir morphology can be estimated using Equation 6.6, whose parameter (K_α) is computed using the morphology in both construction and bathymetry years (see Table 6.1).

$$\Delta SC/SC(t) = -\left[\bar{\xi}_{rec}.\sum R(\Delta t)_{rec}\right] - \left[\xi_{old}.\sum R(\Delta t)_{old}\right] \tag{6.5}$$

$$Ln\left[\frac{\alpha(t)}{\alpha_0}\right] = -K_\alpha.\frac{\Delta SC(t)}{SC_0} \tag{6.6}$$

The key dynamical quantities to assess the impact of siltation on water yield using the VYELAS model are the reservoir storage capacity and its respective morphological parameter α. In the analysis, we assume stationary climate.

Equation 6.3 is used to assess the storage capacity 30 years after the bathymetric survey. For scenario 1, we assume ξ equal to the average ξ_{old}, whereas for scenario 2, ξ equals the average ξ_{rec}. The changes in morphology (α) are computed using Equation 6.6 with parameter K_α derived from the period between inauguration and bathymetry years for each reservoir. We assume that the difference of parameter K_α within three decades for both scenarios is negligible.

6.3 Results

6.3.1 ANN test of hypothesis

The results of the ANN emulations in Figure 6.2 (the boldness of the graphs reflect the degree of uncertainty of the networks) are mostly concordant for both data augmentation types, with some inconsistencies for the MLP warp, probably caused by higher outlier sensitivity (Khamis et al., 2005). LSTMs demonstrate a way lower change for post-1990 data, presumably as they are more robust to short-run deviations compared to the other ANNs (Shah et al., 2018).

Siltation per decade is stable at low positive rate for all network types for most of the decades, as Figure 6.2 demonstrates. With the onset of the water management change in the beginning of the 1990s, the sedimentation rate experiences a steep rise for most of the networks (excluding LSTMs). The decadal siltation reaches 20% for the reservoirs managed completely under the new directive. The networks derived that there exists a substantial difference in decadal siltation for the pre- and the post-1993 condition. The network metrics correspond with and are based on the same character as the ones described by Landwehr et al. (2020). This confirms the hypothesis that the siltation patterns differ before and after the implementation of the management system.

6.3.2 Oversiltation impact on water yield

Table 6.1 presents the main results concerning the historical siltation between inauguration and bathymetry years. On average, the 141 reservoirs silted 10% (total SC reduced from 19.5 to 17.5 km^3) in the mean period of 40 years (1973 - 2013). The decadal siltation rate (r) averages 2.7% per decade, but the individual values vary considerably (from 0.2% to 56.6% every ten years), so that the coefficient of variation surpasses 1.3. This significant variation is associated with the geological, topographical, preservational, and hydrological (mainly the density of small dams upstream) features of each catchment area.

Table 6.1 also shows the temporal changes of the morphological flatness of the reservoirs (α). The mean historical values of the parameter α increase from 9,211 to 10,710, i.e., 16% increment over four decades, on average. In general, the α values increased from 2% to 30%, however, in some cases, the flatness almost doubled, as in the Varzea Volta Reservoir. Likewise, the parameter K_α (average of 1.890) varies largely, from 0.003 to 4.914, with coefficient of variation of 0.75. In general, the morphological flatness of the reservoirs is increasingly

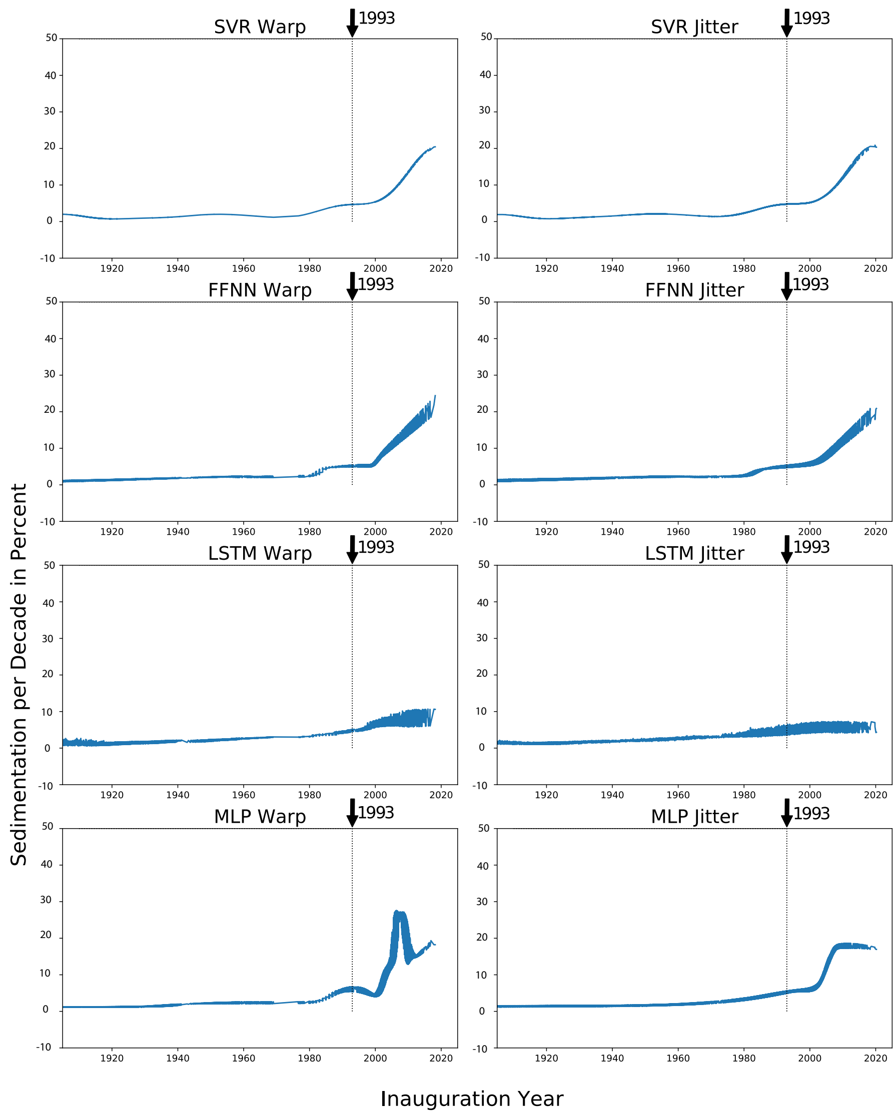

Figure 6.2: Results of Artificial Neural Networks concerning the decadal siltation rate in the State of Ceará

related with the storage capacity. The parameter (α) of the 10% (14) largest reservoirs averaged almost 21,000 in the construction year, but over 23,000 in the bathymetry year; whereas for the 10% (14) smallest dams, the α values are 1,160 and 1,573, respectively. Despite this trend, outliers are frequent due to local relief conditions. For example, relatively small dams may have α values similar to the largest ones, as are the cases of Lima Campos (the 33rd largest) and Varzea Volta (only the 93rd largest) reservoirs.

From Figure 6.3 one can depict that the annual erosivity in Ceará is high (up to 12,000 $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$) with significant spatial variation: the maximum R values are more than twice the lowest ones. Erosivity is maximum in the relatively wet northwestern and coastal regions, surpassing 10,000 $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$. The low-erosivity region is mainly located in the very dry central and southwestern region of the State, where R is usually lower than 6,000 $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$. The sub-humid southeastern region represents well the average erosivity of the State. The comparison of erosivity in both analysis periods (1911-1992 and 1993-2015) shows that the average values did not change, except for the area in the central western region, where R reduced from 10,000-12,000 to 7,000-8,000 $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$. For the whole analysis period, the State erosivity averages 6,278 $MJ.ha^{-1}.mm.h^{-1}.yr^{-1}$.

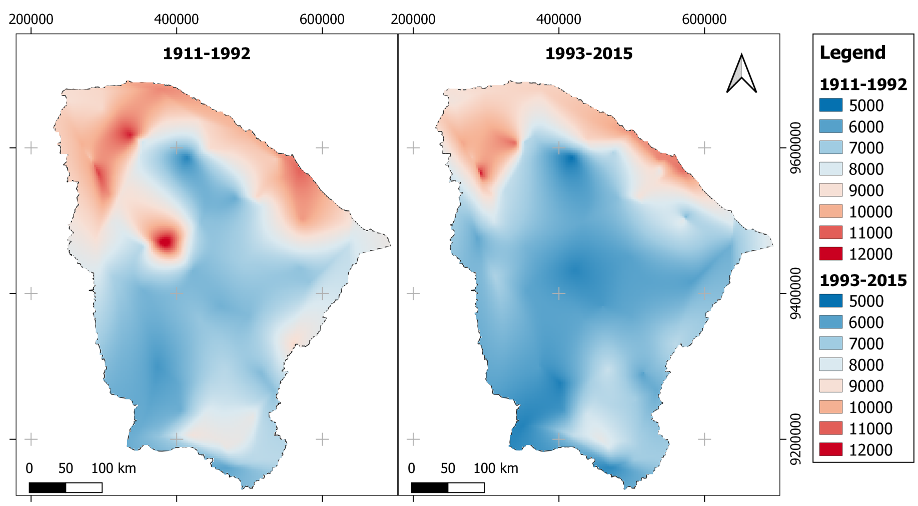

Figure 6.3: Average yearly erosivity over the State of Ceará from the periods of 1911-1992 (left) and 1993-2015(right).

The results of the scenarios analysis can be depicted from Table 6.3 and Figure 6.4. The storage capacity of the 141 reservoirs, which totalled 17.5 km^3 in the bathymetry years, is expected to reduce to 14.9 km^3 according to scenario 1, and to 13.8 km^3, should scenario 2 occur. This represents a considerable loss of volume in only three decades: 15% and 21% for scenarios 1 and 2, respectively. The enhanced siltation pattern of scenario 2 is also expected to deliver more open morphology (higher α values) in the reservoirs than in scenario 1: on average, 17,666 and 15,002, respectively. The direct result of this pattern is the occurrence of higher evaporation discharges from the lakes with time. The trend of higher α values in the largest reservoirs also prevails in the scenarios. However, the difference of flatness among large and small reservoirs tend to attenuate with siltation intensity: the ratio between α in the 10% largest and in the 10% smallest reservoirs reduce from 15.02 to 14.88 for scenarios 1 and 2, respectively.

Based on the results of Table 6.3, we observe that, for scenario 2, i.e., after the implementation of the water management system, the capacity of delivering water with high reliability (Q_{90}) decreases. The average water availability reduction due to oversiltation in 30 years is 6%: from 31.8 to 29.9 $hm^3.yr^{-1}$ per reservoir. Figure 6.4 displays the water availability reduction in scenario 2, when compared with scenario 1, which is expected to occur for all monitored reservoirs, without exception. In extreme cases, siltation can cause the reduction of more than 50% of the water yield within three decades. From Figure 6.4 one can observe that the impact of oversiltation on water yield (i.e., the difference between Q_{90} for both scenarios) affects more severely the smaller reservoirs, which may bring further difficulties for the sparse rural population: the difference is notably larger for the14 smallest than for the 14 largest dams, for example. Figure 6.4 and Table 6.3 also show a relevant hydrological feature in the Brazilian drylands, where water availability (Q_{90}) averages only 20% and rarely reaches half of the inflow discharge (Q_{in}), whatever the scenario. It is also notable that smaller reservoirs have lower hydrological efficiency (Q_{90}/Qin), mainly due to their small depths associated with high local evaporation rates. However, there are exceptions, such as the Lima Campos reservoir (Table 6.3), one of the 25% largest reservoirs, whose hydrological efficiency is as low as that of the smallest ones. In fact, in scenario 1, the 10% (14) largest reservoirs yield 39% of the inflow discharge, whereas the 10% (14) smallest ones only yield 12%. In scenario 2, the efficiency rates reduce even further: 37% and 10% for the largest and smallest dams, respectively.

6.4 Discussion

Due to the intermittence of the rivers and to the quali-quantitative limitation of groundwater, on-river reservoirs generated by dams have been the most relevant form of supplying water in the semiarid Brazilian region, where the State of Ceará is located. As a reservoir reduces its storage capacity due to the sediment trapping, its morphology tends to become flatter, which implies larger evaporation discharges. Besides, siltation also reduces its capacity to store water in the rainy season. Therefore, if the hydrological and water use conditions do not change, siltation may cause an increase of spilling. The long-term water balance of reservoirs shows that the inflow discharge has four main destinations: withdrawal, evaporation, spilling (Campos, 2010) and, less important, infiltration (Mamede et al., 2012). The increment of evaporation and spilling, thus, tends

		Scenario 1				Scenario 2				
Ranking	Reservoir	SC (hm^3)	α (-)	Q_{90} (hm^3/yr)	Q_{90}/Q_{in}	SC (hm^3)	α (-)	Q_{90} (hm^3/yr)	Q_{90}/Q_{in}	δQ_{90}
1	Castanhao	4,982	38,184	1,625.3	0.48	4,650	38,977	1,556.9	0.46	-4%
4	Araras	698	25,079	206.0	0.43	627	26,225	192.6	0.40	-6%
8	Pentecoste	308	59,075	90.1	0.32	286	69,023	82.9	0.29	-8%
17	Aracoiaba	127	8,351	38.9	0.38	115	9,176	36.1	0.36	-7%
33	Lima Campos	53	56,463	4.7	0.18	49	72,754	3.5	0.13	-26%
41	Varzea Boi	42	19,664	12.1	0.23	40	20,826	11.4	0.21	-6%
52	Malcozinhado	27	17,804	8.7	0.15	24	20,604	7.6	0.13	-12%
93	Varzea Volta	9	48,542	2.9	0.05	8	67,210	2.3	0.04	-22%
111	Bonito	4.5	15,285	0.5	0.09	4.0	20,628	0.24	0.04	-50%
141	Aiuaba	0.050	1,121	0.01	0.02	0.046	1,423	0.007	0.01	-30%
Average (n = 141)		106	15,002	31.8	0.214	98	17,666	29.9	0.199	-6%
St dev (n = 141)		460	17,863	152.4	0.128	429	22,009	145.2	0.126	-5%
CV (n = 141)		4.34	1.19	4.79	0.583	4.36	1.25	4.86	0.633	0.896
Minimum (n = 141)		0.050	156	0.002	0.004	0.046	161	0.002	0.003	-68%
Maximum (n = 141)		4,982	112,104	1,625.3	0.528	4,650	141,077	1,557	0.519	-2%

Table 6.3: Simulated storage capacity (SC), morphological parameter (α), water yield (Q_{90}), and its ratio to the average inflow (Q_{in}) for two 30-year horizon scenarios. The last column shows the Q_{90} relative difference between the scenarios ($\delta\ Q_{90}$). The upper part of the table shows specific results for ten selected reservoirs, whereas the lower part shows the main statistical parameters.

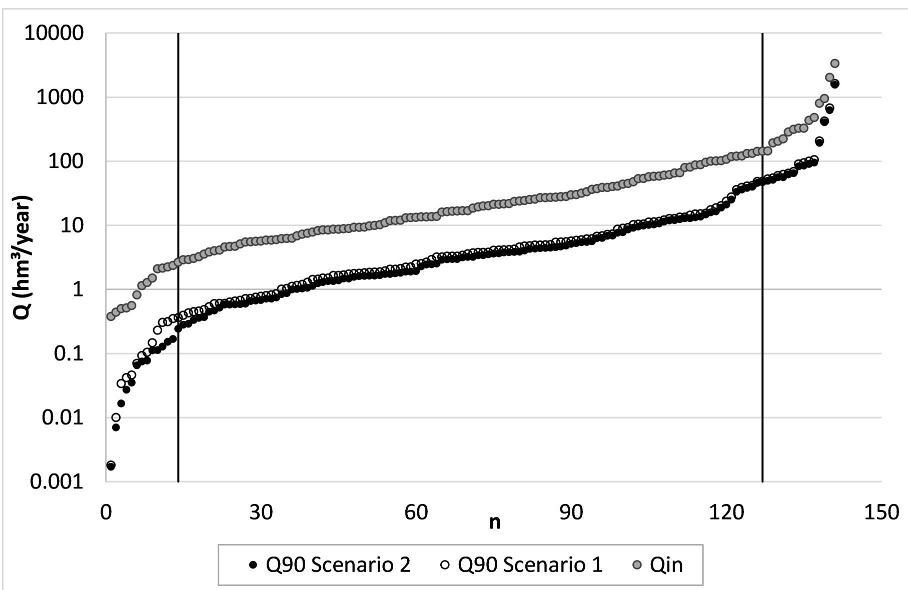

Figure 6.4: Cumulative water yield with 90% reliability Q_{90} for both scenarios 1 and 2 compared with long-term average inflow Q_{in}. The X-axis represents the 141 reservoirs in ascending order. The vertical lines highlight the 14 (10%) smallest and the 14 largest reservoirs.

to cause reduction of water yield, as proven elsewhere (de Araujo et al., 2006). Some argue that the dense network of small dams in the Brazilian semiarid region harm the sustainability of the water system. However, several researchers prove otherwise (Mamede et al., 2012; Malveira et al., 2012; Peter et al., 2014; Nascimento et al., 2019). Lima Neto et al. (2011) argue that, among the benefits of the small dams, there is the fact that they trap almost 60% of the sediment yield, reducing the siltation of the middle-sized and large reservoirs and, thus, benefiting the whole system in the long run.

Data from Table 6.1 show that, on average, the reservoir network storage capacity decays by 2.7% per decade in the State. de Araujo et al. (2006) measured siltation in seven reservoirs in the same State and concluded that, on average, the decadal siltation rate was almost 2%, thus, lower than the results from this research. The reason for the difference of the siltation rates may derive from the representativeness of the data set (the previous work sampled only seven reservoirs against 141 here), but it may also be related with the time of the bathymetric surveys: de Araujo et al. (2006) surveyed the reservoirs few years after the establishment of the water management system, whereas in the present research the time lag was, on average, two decades. The ANN results (Figure 3) for eight different configurations confirm the assumption that the siltation after 1993 is significantly higher than before the implementation of the water management system.

Scenario 1, despite the assumption of lower siltation rate, shows that storage capacity in the State can reduce by 15% within three decades (Table 2), which is of serious concern, especially considering that surface reservoirs (as the 141 ones investigated here) respond to 90% of the State water demand. In scenario 2, the situation is even more drastic, with expected reduction of 21% of the storage capacity in 30 years. In the scenario analysis (Figure 6.4), it is clear that the water availability reduction is more pronounced in the small reservoirs, which are the ones that already dry out more often (Brasil and Medeiros, 2020; Medeiros and Sivapalan, 2020). Additionally, reservoir morphological flatness parameter α increases with the siltation rate. Reservoirs with higher α are more prone to evaporate, which is also a relevant factor influencing the decrease of water availability. This means that, for scenario 2 (i.e., higher siltation rate) more open morphology is expected with time, leading to higher evaporation and, thus, to lower water yield. In the Brazilian drylands, water availability of surface reservoirs represents only a limited fraction of its natural river inflow, ranging typically from 20% to 50%. It is important to stress that the present analysis assumes stationary climate, i.e., both the evaporation rate and average the inflow discharge (Qin) are assumed invariant for the next three decades. If climate change is regarded, however, evaporation augmentation and inflow reduction (Krol et al., 2011) may engender even more severe impacts on water availability with time (Abbaspour et al., 2009; Faramarzi et al., 2013; Greve and Seneviratne, 2015; Donat et al., 2016; Biglarbeigi et al., 2020; Padrón et al., 2020). Table 6.3 shows that, on average, water availability decays by 6% for scenario 2 compared with scenario 1. For the analyzed data set, the global Q_{90} reduces from 4,484 to 4,216 $hm^3.yr^{-1}$, generating a deficit of 268 $hm^3.yr^{-1}$, enough to supply water to the entire State rural population.

The implementation of the water-management system in Brazil (and, in particular, in Ceará) gained credibility among the water users due to a series of factors, such as the availability of information and the organization of frequent and democratic meetings, where effective decisions are made (Campos, 2015; Taddei, 2011). In addition, the water discharge released from the reservoirs (Broad et al., 2007), considered by many the most relevant decision taken in the annual representative seminars, has been respected by the operators, with variation of 10% at the highest (de Araújo and Bronstert, 2016). Considering the fact that, with regard to water, the semiarid region is *offer constrained* (Taddei, 2011), users try to get their total demand, which is usually not possible (Salinas et al., 2019), but the committees tend to approve the annual withdrawal as high as possible, due to societal pressure (de Araújo and Bronstert, 2016). Therefore, after the implementation of the water-management system, the water outtake from the reservoirs augmented (mainly during the dry season, i.e., in the second semester), when compared with the usual withdrawal before 1993. As a consequence, in the beginning of the rainy seasons, the water reserves are lower, reducing the probability of spilling, the main mechanism of sediment outflow from surface reservoirs. This process enhances the reservoir sediment trap efficiency and, thus, the siltation rate.

In the Brazilian drylands, water users and decision makers often envisage spilling as a *waste* that should be avoided at all cost. This reasoning is focused on the premise that spill water leaves the system to reach the ocean, reducing fresh-water availability for the present and coming years. Nonetheless, spilling must be accounted for, to a certain extent, as advantageous (Kim et al., 2020; Mozafari and Zabihi, 2020). It expels a large amount of sediment (Garcia, 2008), extending the lifespan of reservoirs and reducing the temporal rate of water-availability curtailment (de Araujo et al., 2006). Spilling also tends to reduce water pollution. First, because it flushes pollutants from the reservoir, whereas evaporation only reduces the water content, thus, enhancing constituents concentration. Secondly, because spilling diminishes the residence time within the reservoirs, which is of paramount relevance to improve water quality (Soares et al., 2012). Another environmental problem caused by reduction of spilling is the increment of river intermittence (Barnett and Pierce, 2008; Döll and Schmied, 2012), which has considerable socio-ecological consequences (Acuña et al., 2014; Datry et al., 2018). The paradigm that spilling is simply a loss of water is erroneous and over-withdrawing reservoir water may cause serious drawbacks, including oversiltation and depletion of water quality and quantity. Besides including spilling as a partially beneficial process in the water-management system, other measures should be adopted to compensate for the water losses due to reservoirs oversiltation. First, erosion can be more effectively controlled, thus reducing sediment input to the reservoirs. There are several successful experiences of erosion control that could be applied to the State of Ceará (Rickson, 2014; Navarro-Hevia et al., 2014; Simplício et al., 2020). In fact, dos Santos et al. (2017) studied the influence of land use on sediment yield during six years in small watersheds located in Ceará. The authors observe that native Caatinga forest in the experimental site yields 124 Mg.km^{-2}.yr^{-1}, that the practice of burning the field enhances SY by 6%, but that the forest *thinning* reduces it by 37%.

Sediment reuse from reservoirs consists of dredging fertile sediment deposits from inside the reservoirs to make them available for agricultural production. It has proven to be a viable solution for semiarid small dams (Braga et al., 2019), which are the most vulnerable ones, and is possibly part of the solution to oversiltation of large dams, as well. The Brazilian semiarid society should also seriously implement a water-demand management system (Butler and Memon, 2005), including water reuse (Wilcox et al., 2016). These strategies can help the Brazilian dryland society adapt to decreasing water availability in the next decades (Manabe et al., 2004; Seager et al., 2013; Kumar et al., 2014; Sharafatmandrad and Mashizi, 2020).

6.5 Conclusions

In the Brazilian semiarid State of Ceará, artificial neural network analysis based on data from 141 monitored reservoirs show that their silting rate significantly increased after the implementation of the water management system in 1993. The *rationalization* of water use enhances withdrawal, which reduces the outflow rate and, thus, augments the reservoir sediment trap efficiency. These results attest that spill from the reservoirs cannot be seen simply as water loss, but as a positive asset, an effective mechanism that reduces siltation and improves both water quantity and quality. It is known that siltation diminishes not only the reservoir storage capacity, but also its water yield: in the study area, the 90%-reliability discharge from the reservoirs is expected to decay by 6% within 30 years, which is enough to supply water to the whole State rural population. Therefore, in the focus region, the implementation of the management system contributes to the reduction of water offer, whereas the demand is expected to increase with time. To help compensating for the water losses caused by the excessive siltation, four measures are recommended: to include reservoir spilling in the operation rules, to reduce erosion in the basins, to execute a sediment reuse policy, and to implement water-demand management.

6.6 Declarations

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Conflicts of interest/Competing interests

We declare no conflict of interests/competing interests.

Availability of data and material

We declare data transparency and availability upon request.

Code availability

We declare code transparency and availability upon request.

Authors' contributions

All authors (José Carlos de Araújo, Tobias Landwehr, Pedro H. L. Alencar and Walt D. Paulino) made substantial contributions to the research.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. No humans or animals were involved as research subjects/objects.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent to publish

The participants have consented to the submission of the article to the journal.

CHAPTER

7

DISCUSSION AND CONCLUSION

This chapter provides a summary, a critical discussion of the results with respect to the initial research questions, concluding remarks and outlooks on further possible research steps. As each chapter already comprises a detailed discussion, the focus here is exclusively on the results directly related to the research questions.

7.1 Summary

Figure 1.4 from Chapter 1.3 reflects various stages before and after (management) action is taken. Each of the studies presented in this dissertation refers to one of those levels that range from a coordinating macro aspect to the meso effects of on-site action.

Chapter 2 centers on the level of security assessment. It is formed upon existing energy-water dependency research and defines the base line of security research for the energy-water context. The chapter's research draws upon this definition and a framework of inter-dependencies between electricity generation and water supply to form a set of main- and sub-indicators for the evaluation of regional energy-water security. The main indicators (Constraints on Water, Dependency on Water, Institutional Capacity, Competition for Water, Feedback Effects, Water Footprint from Figure 2.5 and Figure 2.6) demonstrate the holism of the set. Each main indicator is fleshed out with two to four carefully reasoned sub-indicators. The system allows the region-based evaluation water-dependent electricity generation. It tells users whether current and upcoming electricity infrastructure and/or administration and/or jurisdiction will cause major negative and non-secure impacts in one of the main indicator categories. The chapter's research fits perfectly into the macro level aspect of security/ sustainability and delivers answers sought by **Q1**, which will be discussed in Chapter 7.2.1.

Chapter 3 treats the meso level of transference of strategies towards on-site (management) action. It researches major bottlenecks for strategy transference and implementation and finds them in an alienation between front-end administration practitioners, the public professionals (PPs), and other stakeholder groups, summarized as citizens. The alienation manifests in both vertical and horizontal governance direction and impedes effective strategy implementation on the on-site level of a WEF-challenge. It was named the verto-horizontal disconnect. The disconnect blocks individual on-site solutions and favors thus panacea approaches and vice versa. A proposed methodology to overcome the verto-horizontal disconnect are public action situation encounters. The chapter identifies the verto-horizontal disconnect in a case study in the Middle Drâa Valley around Ouarzazate, Morocco. To investigate whether it may be downsized by public action situation encounters, the methodology was realized in the MDV and subsequently analyzed. The results demonstrate that a reduction of the verto-horizontal disconnect between PPs and citizens is feasible. However, it was also visible that the panacea approaches are rooted within both PPs and citizens, which keeps up the disconnect. With the MDV case study, the chapter's research illustrates intriguingly the challenges of meso level strategy transference. It thus delivers meaningful answers to research question **Q2**.

Chapter 4 deals with the meso level of the mindset of an action, which determines the way in which strategies are executed on the micro level. It investigates whether, and how far, sustainability or security thinking is existent within the implementation of (management) action. The optimism bias is identified as a prevailing and underlying psychological mindset in infrastructure planning, management and operation. This includes also the energy-water security endangering effect of reservoir sedimentation, which is used to investigate the optimism bias. To identify its extent, a database is formed that allows researchers to evaluate the optimism bias mindset. The database encompasses a vast Japanese reservoir sedimentation data pool (1000 reservoirs), which is evaluated against a maximum sedimentation threshold that was determined by the Japanese governance. Various different Artificial Neural Networks (ANNs) are utilized as methodology to derive the non-linear relationship of sedimentation. Their emulation results were verified on the sedimentation directives. The results demonstrate that optimism bias is a prevalent and continuous mindset within Japanese reservoir management with a trend of (yet insufficient) refraining from this mindset. Though the Japanese research is exemplary and advanced in researching managing and monitoring the reservoir sedimentation (Kondolf et al., 2014; Morris, 2020), the optimism bias persists. Other societies with less research, management and monitoring are thus presumed to suffer even more from optimism-biased planning, management and operation. The chapter's research demonstrates vividly how an (un)conscious mindset negatively influences security/ sustainability management action for a concrete energy-water context problem and therefore delivers an important response to research question **Q3**.

Chapter 5 is focused on the meso effects of on-site management action. It surveys how far the effect of such management action is palpable on the meso level and how far it contributes to sustainability. Again, management actions against reservoir sedimentation and a concrete energy-water context challenge are surveyed. Compared to Chapter 4 an even more vast sedimentation data set that incorporates the specific sedimentation time series of 1225 reservoirs over 18 years from Japan is established. The set moreover encompasses notifications of concrete management actions which are supposed to have a positive effect on sedimentation and hence the reservoirs' security/ sustainability. ANNs were again used as a major analytical tool to derive evidence from the data. This time, the focus was laid upon Gated Recurrent Units (GRUs) that are ideally suited to learn from time series data as they possess an integrated memory function. The networks learned influence patterns of the management action from the data set and demonstrate the sedimentation reducing or - in the case of some actions - sedimentation enforcing character. As it is derived on the meso level of a region/an entire country, the results present a generalized view of sedimentation management action effect and thus they exclude the influence of case-based specificity. The Chapter's research delivers therefore intriguing answers to the research question **Q4**.

Like Chapter 5, Chapter 6 also deals with the meso effects of on-site management action. Likewise, the reservoir sedimentation is surveyed as a concrete on-site management action issue of the energy-water context, namely the effect of a new water management directive on reservoir management in the Brazilian state of Ceará was surveyed. A set of 141 reservoirs was formed. It possesses less data entries than the sets of Chapter 4 and 5 and also less continuity. Fortunately, an ANN methodology very similar to the one of Chapter 4 proved capable of carrying out a methodological analysis of presumed management impact by focusing on the sedimentation per decade. It was shown that, apart from the onset of management integration, a rise in sedimentation per decade is observable. The research co-authors subsequently specified the water-availability reduction of 6% in 30 years due to intensified sedimentation, using VYELAS, a specific Monte Carlo based model (de Araujo et al., 2006). The chapter's research presumes the reason behind the sediment increase in a higher rationalization of the water resources which increases the sediment trap efficiency and moreover, decreases opportunities to lose sediment via spilling. The rationalization, however, has been initiated as a response to the naturally scarce water availability in Ceará to secure water supply. The chapter's research thus demonstrates goal conflicts for the effects of sustainable and security aimed management action on the meso level and delivers answers to research question **Q4**.

7.2 Discussion

Chapter 7.1 and 1.3 already hinted at the fact that there will not be 100% clear answers to the research questions which are settled in a multifaceted environment. This refers to both a) the multi-leveled and vaguely framed definitions of sustainability, security and the WEF-Nexus (Chapters 1.2.1, 1.2.3 and 1.2.2), in which they reside; and b) the complex interplay of individual on-site challenges within the energy-water context. The results produced by the particular chapters are nonetheless intriguing and their implications for the research questions thus subject to close examination and discussion.

7.2.1 Q1 - The macro level of security and the efficiency of assessment

Research question **Q1** was formed under the special impression of the SDGs (Caballero, 2016), their vagueness (Bali Swain, 2018; Purvis et al., 2019), the inconsistencies between SDG-targets and the lack of cross-SDG foci (Nilsson et al., 2016; Barbier and Burgess, 2019). A cross-SDG issue like the energy-water context was simply not reflected by the most important tool for sustainability assessment and strategy formation on a global level (Katila et al., 2019; Farnia et al., 2019; Turcea and Ion, 2020). Consequently, **Q1** is essential for the energy-water context and - as demonstrated in Chapter 1.2.3 - for energy-water security:

> ***Q1.*** *How does a definition and assessment for the security of the energy-water dependency for all electricity generation types look?*

This question incorporates various important parts. First, it demands a definition of energy-water security. The definition is given in Chapter 2.3.2, but is it the only valid definition for the energy-water context? Most likely not.

The respective energy and water security definitions (Chapter 2.3.2) are an argument against it. There is a wide plurality for both of the context's major elements that is scientifically accepted or debated and there is no reason why a combination of both issues would reduce the flock of definitions. An example is the W4EF assessment set (Lemoine and Bellet, 2015b,a) with its very technical approach that certainly does not attribute to the holistically outlined definition from Chapter 2.3.2 that is based on Grey and Sadoff (2007).

So why would the definition from Chapter 1.3.1 protrude from the definition forest? It is the holistic element of the research question and the approach to view electricity generation. The holism is rooted in a requirement to reflect all water-dependent links of all major electricity generation types.

The Figure 2.4 illustrates the wide range of inter-dependencies that were identified. Especially with Figure 2.4 it is easy to see how the two-dimensional energy-water issue branches into further topics: From agriculture (Flörke et al., 2018; Abd Ellah, 2020) over governance (Pahl-Wostl, 2015) to land-use management (Diekkrüger et al., 2010; Snoussi et al., 2002). Rapidly, one has to either cut off all the branches to focus on the trunk (like e.g. W4EF from Lemoine and Bellet (2015b)) or one has to incorporate the whole or a grand part of the complicated network.

If one decides on the latter, the integration of the whole network, one rapidly ends up in holism, as can be seen by Shore (1999) who argues that

> *(...)holism requires a genuine tolerance for complexity, a recognition of tie limits as well as the power of our claims, a willingness to learn several different but complementary paradigms and a basic theoretical commitment to systematically relate those perspectives to each other and to a body of empirical data.*
>
> Shore (1999)

The modified definition of Grey and Sadoff (2007) from Chapter 2.3.2 reflects exactly those characteristics of holism: a) a "genuine tolerance of complexity" and b) a "willingness to learn several different but complementary paradigms". Those two conditions are vividly illustrated by Figure 2.4, that reflects the complexity of different, but complementary, paradigms around water-dependent electricity generation. Accordingly, it can be said that the modified security definition of Grey and Sadoff (2007) is in its holism the most natural security definition to **Q1**.

The assessment system from Chapter 2.5 logically grows on the modified definition of Grey and Sadoff (2007). For all its inherent logic, the system is most likely not a unique answer to **Q1**. This is already reasoned by the inevitable bias of subjectivity and selectionism that Arndt et al. (2006) detects when they state that *a perfect indicator set will never be found*.

The indicator set of Chapter 2.5 is therefore most likely not the only form to create a holistic indicator set that corresponds with **Q1**. For example, there is a diverging opinion about quantitative indicator efficiency. van Doorn-Klomberg et al. (2013) argue for a medical research that indicator composites of five to seven indicators can have much the same precision of measurement as larger sets. Small numbers of indicators would already possess a formative character. The indicator set from Chapter 2.5 possesses, however, six main indicators and altogether 16 sub indicators. Following van Doorn-Klomberg et al. (2013), a smaller indicator set might just be more efficient and reasonable.

On the other hand, van Doorn-Klomberg et al. (2013) argue that much is dependent on the a priori reasons of indicator set creation. As reasoned carefully in Chapter 2.4 the different main indicators are a logical a priori condition of the holistic energy-water context. Does the developed indicator set then contradict van Doorn-Klomberg et al. (2013)? Not if each main indicator would be regarded separately. Each sub-indicator set would correspond in its reduced number (two to four) with the formative efficiency of reduced indicator quantity that van Doorn-Klomberg et al. (2013) demand. Nevertheless, it must be agreed that other interpretations of indicator efficiency are possible. Hence, other indicator set compositions are plausible too.

So the response to **Q1** delivered by Chapter 2 might just be one of many possible answers, but it is a very plausible one when regarded in the light of holism and efficiency. Though much may be debated, e.g. the data availability for some sub-indicators or their in-detail composition, the overall picture of the set is a rather motivating one: The set is flexible between regions and it is flexible against all sorts of energy generation types, whilst the indicators as such keep on being quantitatively efficient, if the main indicators are seen as a logical a priori condition. The set tries to demand only generally available data or settles on already existent data systems without trying to be too technical and too superficial. It tries to bridge science and politics and decision-making. Hence, it tries to pave the way from overall sustainable and security analysis to strategy transference for energy-water context. The set is thus an important part of the leveled application process of Figure 1.4 - and therefore, it is not *the*, but *a* very worthwhile response to **Q1**.

7.2.2 Q2 - The meso level of transference and the authority of stakeholders

The second research question **Q2** is rooted in the continuous challenge of transferring overarching assessment concepts like the SDGs to on-site action. The lack of transference is in fact one of the main critiques on the SDGs (Easterly, 2015; Purvis et al., 2019). The SDGs' inherent structure is one of the main reasons for the lack of transference (Bali Swain, 2018). Other major reasons, that cause non- or insufficient implementation of concepts and strategies, are sustainable/securlances (Faysse, 2015; Faysse et al., 2018; Silva et al., 2019; Pahl-Wostl, 2019). For the energy-water context, this led to research question **Q2**.

> ***Q2***. *How to overcome sustainable/securlances to transfer security aspects to on-site action in the energy-water context?*

Chapter 3 introduced the verto-horizontal disconnect, to reflect a certain type of content transference gap, namely the one between Public Professionals (PPs), the agents of public administrations (Stillman II, 2017; Jacob, 1969), and further stakeholders summarized as citizens. Various types of obstacles presented in Chapter 3.3 largely oppose the transference of security and sustainability concepts and strategies to practical on-site action. The dissertation responds to this situation via the introduction of public action situation encounters, a pragmatic and participatory approach (Godfrey and Lewis, 2018; Pahl-Wostl, 2019) to remedy the disconnect. The methodology proves to be a viable tool, as results show (Chapter 3.5). Is the methodology thus a gold standard for strategy transference and thus *the* answer to the research question **Q2**?

A short contemplation of the panacea thinking, which the methodology tries to oppose, shows that a singularity response of only one correct methodology is - by logic - not existent. Panacea in governance incorporates the trend to one/few-solution-for-all-problems approaches (Ostrom, 2007; Ostrom and Cox, 2010; Pahl-Wostl, 2019). Public action situation encounters try to remedy strategy transference challenges by opening a space that gives room for high solution flexibility between PPs and citizens, both in extent and quantity.

The claim to be the only viable response to **Q2** would thus be inherently self-contradicting to the principle of the methodology. It is thus valid to say that stakeholder imbalances in the energy-water context can and must be overcome with other methodologies.

What is correct to say is that the dissertation found a worthwhile approach to induce flexible strategy transference to on-site action. As similar approaches are barely existent in the region, the public action situation encounters appear to be promising especially for the MENA region, since it would fill a participatory gap that is in other regions of the world not that vast (Terrapon-Pfaff et al., 2018; Faysse et al., 2018; Fayiah et al., 2020). The dissertation's content is thus especially novel here. Public action situation encounters would help to abate the strong conviction for panacea approaches, that were detected in Chapter 3.6.2 to be strongly emergent among both PPs and citizens, in the MENA region.

It is, however, necessary to emphasize that the true effect of public action situation encounters on on-site action in the on-going process of WEF-challenge management of the Middle Drâa Valley (MDV) case study needs to be further evaluated. Though a reduced verto-horizontal disconnect was detected among PPs and citizens, this does not necessarily mean that the disconnect will manifest itself in practical action. The process of on-site implementation is a long-lasting process that might need years and thus demands a time-frame concordant observation and evaluation. This is, however, beyond the scope of the dissertation.

Nevertheless, presumptions can be made; for instance, referring to the role of certain stakeholder groups. Schöbel et al. (2016) demonstrated that the influence of other people on decisions and decisions-makers is higher the higher the perceived authority of the particular person. This would especially hold true if the person with authority would have an opposing opportunity to the one of the decision-maker's, according to Schöbel et al. (2016).

Transferred to the situation of a public action situation encounter, this would mean that PPs and citizens would let themselves be influenced by the other, the higher the perception of the other one's authority. Now the question is: how much authority do both groups attribute to one another? Spierings (2019) delivers hints for the MENA region that serve to partially respond to this question.

According to Spierings (2019)'s research, the MENA region demonstrates a rising distrust between people, the more educated they are and the better they are positioned in life. This distrust appears to be directly and negatively connected to the intensity of the authoritarianism in a MENA country. Consequently, the distrust in authorities, i.e. PPs, of that country, would be high and the actually attributed authority to authorities low. Morocco and thus the MDV are still affected by a considerable degree of authoritarianism (Mo Ibrahim Foundation, 2019). Morocco and the MENA region hence appear to be an unfavorable condition for a public action situation encounter to induce strategy transference as the mutual low authority perception would block the process. It is thus important to lower authoritarianism and elevate mutual trust in the mutual authority to enforce the effect of public action situation encounters and thus strategy transference.

Even under unfavorable conditions, the public action situation encounters serve as a viable tool. As Figure 3.8 demonstrates, the mutual opinion and understanding of the other stakeholders and their respective view on the MDV WEF-challenge was positively influenced due to the effects of the format. This means that the concept itself - in its limited size - is able to create a microbiome of mutual respect. This microbiome is then suited to be the open parquet floor on which macro scale security and sustainability concepts can be modified and transferred to be eventually implied as on-site (management) action. Due to the upper reasoning, this can be presumed to hold true for the WEF-case of the MDV and thus, it is likely to be a very viable response for **Q2** and other energy-water context challenges.

7.2.3 Q3 - The meso level of mindset and the role of reservoirs

Infrastructure like the one of electricity (and thus also the energy-water context) is under constant implementation, planning, operation, reformation and erection since its invention. It has thus always been applied under a certain mindset - and this long before sustainability or security turned into globally acclaimed and thriving concepts. **Q3** was developed under this impression.

> ***Q3.*** *How to determine a sustainability/ security mindset in management action within the energy-water context?*

If one is to follow Flyvbjerg (2009), infrastructure has been implemented under quite unfavorable conditions over the course of the last decades. The project conditions were such that competition situations artificially induced boasting about projects. This again induced massive risk underestimation and benefit overestimation and a ”survival of the unfittest”, as Flyvbjerg (2009) calls it. The mindset of infrastrucure management is therefore a supreme example of the optimism bias (Kahneman and Tversky, 1979; Kahneman, 2011). Flyvbjerg (2009) defines it to be more or less contrary to sustainability and security implementation.

The survey Flyvbjerg (2009) conducted on infrastructure was made under a business point of view. They found a rather devastating optimism bias. Alongside with Ansar et al. (2014) and under the same perspective they focused - still under a business point of view - on reservoirs to find similar conditions. They showed thus that an important piece of the energy-water infrastructure was economically implemented under an economically non-sustainability/non-security mindset.

Chapter 4 went a step further and surveyed on-going management action, namely against sedimentation, a process that massively endangers the sustainability and security of reservoirs for all of their purposes (among them electricity and water supply) (Annandale, 2013; Morris and Fan, 1998). The optimism bias was surveyed with Artificial Neural Networks on a thorough data set from Japan.

The research was settled upon mass data availability (in the context of sedimentation data - in comparison to other mass data quantities, the treated data in this research was still modest) to derive - over the course of decades - patterns that could be put against management directives. Thus, a legally expected sustainability and security target is controlled against the actual results, revealing the degree of the sustainability and security mindset in actual management action. It is a seldom-utilised opportunity of a long-term goal controlling that reveals an important mindset component, namely the optimism bias. Via the survey a systematic, decade-lasting non-compliance with sedimentation targets could be identified that was attributed to (un)conscious optimism bias. With this, Chapter 4 delivers an intriguing response to **Q3**.

Naturally, this is not the only viable response to **Q3** for the energy-water context. It is the observation of a special compound of management actions (those against sedimentation) in the special case of multi-purpose reservoir infrastructure. However, such long-term, mass data observation for sediment management is to date unique. Chapter 4's answers are not definitive to **Q3** and the energy-water context, but very substantiating, indicating and due to their uniqueness, distinguished ones.

The methodology and results of Chapter 4 might be distinguished, but nonetheless similarities to other energy management research can be detected. On the one hand, the observations derived from Chapter 4.2.7 in Japanese sediment management regarding monitoring and observation (Okano et al., 2004) coincide in their extent roughly with the descriptions made by Steven Fawkes (2001, 2016) for implementation of sustainable concepts of thermal electricity generation in the United Kingdom. Sustainability and security thinking are receiving more and more influence in energy management actions. However, the extent still diverges massively from the overall expectations. This is valid for the results of Chapter 4.3 and findings of Steven Fawkes (2001, 2016). Both researches substantiate that the overall mindset behind management action must (still) be seen as being rooted in non-sustainability/ non-security.

On the other hand, there are the quite advanced approaches of the Japanese scientific and engineering society to cope with sedimentation (Kondolf et al., 2014; Kantoush and Sumi, 2017), that do not completely find their way to implementation. It is presumed that this is linked to the not-yet eradicated business collusion in infrastructure projecting and management in the Japanese economic society, which is conditioned by the strength of economic stakeholders (Kinoshita et al., 2008; Fujii, 2012). Such strong stakeholder influences are seen by Cherp et al. (2017); Fouquet and Pearson (2012) as one of the main reasons for erratic mindsets in energy management. They are thus great inhibitors of sustainable and secure management action.

Flyvbjerg (2009) again states that optimism bias and the "survival of the unfittest" will not be overcome as long as such strong stakeholders superficially work under the ethics of sustainability and security, while they are in reality rather driven by a striving for funding and revenue. Subsequently, it can be supposed that the advanced Japanese sedimentation management mindsets are undermined by non-sustainability mindsets of strong stakeholders. Chapter 4.4.6's presumption reflects exactly this when it assumes that reforms in the Japanese competition law have not yet had any impact on better sedimentation management because nothing has effectively changed, for business collusion still prevails in the infrastructure sector and in the governance's, managers' and planners' mindsets. By substantiating this estimation, the research from Chapter 4 is indeed a very valuable one to **Q3**.

7.2.4 Q4 - The meso outcome level of effect and Artificial Neural Networks

In the very same manner that management action has always been under a certain mindset, such management action always has had a certain effect. Especially interesting is to control the outcome of management action that has been executed under a certain aspect of sustainability and security. From this, research question **Q4** originated.

> ***Q4.*** *How to determine the sustainability/security impact of single management actions for the energy-water context?*

Unlike the other questions, two chapters were dedicated to **Q4**, both of them focusing again on management action against reservoir sedimentation. Chapter 5 surveyed a broader range of concrete on-site action with a broader and more refined data set from Japan, whilst Chapter 6 investigated **Q4** solely a single action directive with a smaller data set from Ceará, Brazil. As the determination of management action on the impact of sustainability/ security was executed via a mass data approach, artificial neural networks (ANNs) played a key role in both cases.

Indeed, mass data neural network approaches proved to be extremely worthwhile for a large variance of complex questions and contexts (Ise and Oba, 2019; Purushotham et al., 2018; Sharma and Om, 2016). They served to visualize and quantify even abstract questions. However, the results of neural networks need to be utilized and interpreted carefully.

Chapter 5.4 is a prime example for this. Its final result is displayed in Table 5.3. As explained already in Chapter 5.4, the more impactful meaning of the said table is not so much embedded in its absolute numbers, but more in the relative comparison of the results. For example, the network learned that *Spilling/Flushing* is 30% efficient than *Dredging*. It must, however, be emphasized that the networks do not attribute for every single reservoir case. Further research has to determine to which extent the efficiency difference is valid for individual use cases. The strength of ANNs is to draw a general picture and to derive statements from complex mass data - ANNs work thus on the meso level (or even a macro one, depending on the extent of data).

The interpretation of this dissertation's ANN results is hence always left to the human mind. So the answer to the "How to determine (...)" part of **Q4** is not simply "a mass data ANN approach". It is the careful use of powerful methodologies accompanied and completed by careful analysis and interpretation. Two of this dissertation's results vividly illustrate this.

There is on the one hand the case of *Sluicing*, which is incorporated under *Flood/Typhoon* in Chapter 5.4. Here, it is necessary to know about the practical usage of sluicing (the active diminution of sediment initiated by operators using intelligently opened reservoir gates prior to or during intense water input events like floods and typhoons) and compare it with the existing data to fully understand the data's significance and to fully interpret the network's results, as done in Chapter 5.4.3. Sedimentation would normally accumulate massively in closed reservoirs during a Flood/Typhoon occasion as such events bear an extremely erosive power. The water that would enter a reservoir during such an event would carry enormous loads of sediments that would sink subsequently. However, in case of *Sluicing*, sediment would get washed out and would thus diminish. In the case of Chapter 5.4.3 the lack of information of how operators reacted to floods/typhoons (sluicing or not) has certainly led to the unclear results the ANNs have produced *Flood/Typhoon* events.

On the other hand, there is Chapter 6. Here, the ANNs detected a massive increase in sedimentation per decade after the year 1993 for the reservoirs in Ceará, Brazil. The ANNs, though, did not reveal the reason for that effect. The careful research and knowledge about sedimentation and reservoir management in this region reveals a coherent explanation for the phenomenon, that was derived from the data: the supply-based water management approach that deemed *Flushing/Spilling* as an unnecessary loss of (scarce) fresh water, entailing none or deficient flushing and spilling - which again led to an increase in sedimentation.

Chapter 6 demonstrates intriguingly how a perceived change towards energy-water management security causes the whole reservoir system to presumably be less energy-water secure in the mid- to long-term future. This is just detected due to ANN mass data effect information extraction and subsequent context-based interpretation. ANNs thus deliver results that possess little meaning if not carefully surveyed and interpreted by the human mind.

ANNs are (yet) no magic black box solution tools, but succumb to various restrictions: be it their architecture (Zador, 2019), or in their data input bias (Sun et al., 2020; Kleinberg et al., 2020). The dissertation has shown advantages and limitations of the ANN methodology to expose the management action effect for two meso outcome scenarios (see Chapters 4 to 6) while responding **Q4**. They are extremely powerful tools to reveal management action effects on the meso level as long as the tool is mastered and led by an analytic, scientific mind. In this combination, the answers delivered by Chapter 5 and 6 are worthwhile in both their content and their formation for detection of management action efficiency in energy-water contexts.

7.2.5 Across the levels: The integrative process of the macro and meso layers that precede and follow the micro point of action

As already mentioned in Chapter 1.3 and demonstrated by the Chapters 7.2.1 to 7.2.4, the dissertation cannot deliver 100%-guaranteed advises about how to tweak, modify and optimize the layered process (Figure 1.4) that precedes and follows management actions in the energy-water context for more security and sustainability. But it does make it palpable and in parts quantifiable. The dissertation demonstrates intriguing insights of how the different layers have their input and output share of realized on-sight management action of a concrete sustainability and security challenge, namely the energy-water context.

To get a sharper picture about the impact of this dissertation's results on multi-leveled governance and management action, a brief and fictive example shall be set up: Let be assumed, stakeholders of a fictive region with a multi-purpose reservoir infrastructure, which is already for some decades in use, want to evaluate how to proceed with their reservoir management strategy for the next few decades.

The multi-level assessment approach from this dissertation's Chapter 2 would now allow to derive a holistically assessed picture of the energy-water context in said region, that determines, where challenges in water supply-security and energy generation exist. It would pinpoint strengths and weaknesses of the (already installed) reservoir infrastructure on the macro level of security by surveying various dimensions such as economy, ecology or technical capability among many others.

According to Chapter 3 these insights could be shared and debated with all relevant stakeholders on the meso level of transference. Their points of view and knowledge would influence the reservoir management strategy development as the gap between the PP and stakeholder citizens would be effectively reduced via processes such as public action situation encounters, which again would aid in revealing possible non-sustainability, non-security unknown unknowns and thus sharpen the future strategy.

Another major step in revealing such unknown unknowns would be reached by integrating methodologies from Chapter 4 that would give information about the meso mindset of the up to date reservoir management strategy. This would effectively bring to light whether a) the up to date reservoir management strategy was optimistically biased and thus ought be adapted to this, and whether b) the outside view would demonstrate unknown unknowns that up to now have not been addressed by said reservoir management strategy allowing a further shaping of the future reservoir management strategy.

Finally, analysis similar to Chapter 5 and 6 about already enacted management action's meso effects would give information about the expectable character and impact of future management action within the upcoming reservoir management strategy. The otherwise difficult to foresee effects in the long-term business of reservoir management in the energy-water context can thus be made palpable by receiving directions of expectation.

The integrated multi-level approach of this dissertation would surely not guarantee to not face any unknown unknowns in a future energy-water context (reservoir) management strategy and its points of on-site action. But a strategy, that was shaped and established based on (similar) methodologies and insights presented in this dissertation, would form a resilient baseline against effects of (partly unknown unknown based) non-sustainability and non-security as outlined in Chapter 3.1 and 2. For the energy-water-context and especially for reservoir management this has been - in this form - unseen before (Kantoush and Sumi, 2019; Schleiss et al., 2010; Morris, 2020).

The dissertation's results therefore present a multi-level tool-set that allows for the realization of multi-level approaches outlined by the seminal concepts of Pahl-Wostl (2019); Daniell and Kay (2017); Ostrom and Cox (2010). The established layered framework of management action (in the energy-water context) depicted by Figure 1.4 forms thus a coherent road-map that can be utilized by practitioners, politicians, researchers and many other stakeholders. Each of the methodologies might stand for itself alone, but just their joint utilization opens a pathway to an impactful, thorough and holistic evaluation of energy-water context challenges. The multi-layered structure thus is a highly recommended approach towards such cross-SDG challenges.

7.3 Outlook and Conclusion: The overall impact of the dissertation

The dissertation surveyed the interface of sustainable electricity generation and its water supply preconditions, going from the very broad and macro of the energy-water relation to succinct cases and the effects of (micro) management action on the meso level. It commenced with security assessment on a holism baseline, and delved into the very concrete energy-water security hazards of reservoir sedimentation. It reflected thus the various levels of governance, management and on-site action as depicted in Figure 1.4, going from the general to the special under a sustainability and security perspective. The dissertation did so in surveying in three different countries with completely different structures and traditions of governance in a different spatial resolution on four differently focused research questions. Thus, the thesis alluded to the energy-water context on an abundance of differently organized and leveled governance structures and systems. It did so, however, without setting any preference on a system or structure.

Though the dissertation encountered the energy-water context on a multi-level format, it prescinds from giving clear recommendations to a certain governance structure or a necessary scaling for energy-water challenges. In this, it conforms with Pahl-Wostl (2015), who stated that a) "[Energy-]Water governance problems are complex and require a multi-level approach" and b) "an optimal spatial scale upon which to govern [energy-]water resources [or contexts] does not exist". Those statements are transferable to the energy-water context, as was indicated with the square brackets. An extreme example for two completely different multi-level governance systems with a reasonable success is e.g. given by Rothstein (2015), who identified the illiberal Chinese autocratic kader system as being equally efficient as liberal democracies in certain aspects of multi-level infrastructure management. It is thus obvious that a single recommendation for a superior multi-level governance system or structure for the energy-water-contexts is bound to be wrong.

Rather than predefining a paved road for energy-water context challenges, this dissertation gave planners, practitioners, operators, managers, decision-makers etc. tools at hand that allow them to flexibly pave their own way of assessment and analysis to eventually imply sustainable and secure strategies for their own challenges within the energy-water context. It did so in particular, but not exclusively for reservoir sedimentation. The dissertation shaped various tools to prepare the ground of multi-level energy-water security governance:

- A flexible and holistic energy-water security assessment system from Chapter 2 that allows to define vast aspects of energy-security for any kind of region
- The public action situation encounter approach from Chapter 3 that allows us to downsize vertical and horizontal differences between stakeholders in manifold energy-water context situations
- The approach of using the optimism bias from Chapter 4 to identify the degree of security and sustainability in energy-water management mindsets
- The application of Artificial Neural Networks in the Chapters 4, 5 and 6 to determine mindsets and effects of concrete energy-water management actions via algorithms that are transferable to other energy-water context issues (reservoirs, thermal energy, everything that generates time series data)

As already pointed out in the Chapters 7.2.1 to 7.2.4, the tools and responses are far from being exhaustive. Further developments are to be expected, further research steps desirable, further investigations needed. Here is a brief listing of outlook topics which makes no claim to completeness:

- The energy-water security assessment system will be discussed by the scientific community after its publication. The assessment system will most likely experience updates as a result of said discussion, but also due to its upcoming application in case studies. Those updates will presumably improve applicability in practice and may introduce some more meaningful or practical forms of data sources.
- The public action situation encounters will evolve in the MENA region, where such approaches were scarce so far; the new results that are about to be produced will allow for broader effect analysis. This will not just

make other statistical evaluation processes possible, but will also offer a broader view on the verto-horizontal disconnect, on WEF-challenges, on the efficiency of over-regional WEF-strategies like the Plan Maroc Vert (Faysse, 2015) and on energy-water security.

- Comparative studies from other countries with sufficient data (like the Swiss (Kondolf et al., 2014; Morris, 2020)) regarding the optimism bias would lead to further insights about the actual prevailing degree of security and sustainability mindset in energy-water security and especially, in sedimentation management.

- Algorithmic improvements for the neural network analysis are in the range of the perceivable. For instance, Generative Adversarial Networks are extremely promising (Gui et al., 2020) in producing realistic artificial data that would help to overcome monitoring gaps for many countries that have not been monitoring sedimentation to a sufficient degree. GANs are mostly applied for image data right now, but their data structure does not differ that much from multi-input time series data: Both are represented by ordered numerical structures. Indeed, within this dissertation, some months have been spent applying this approach, but although cooperation with many GAN experts was established and various approaches undertaken, completely satisfying results could not be reached and so the methodology was discarded for the time being.

- Specific management actions in reservoir siltation would deserve and need more analysis. Sluicing, the reduction of sedimentation prior to and during flood events, is here and for example: There is the need for more precise data (as described in Chapter 5.4.3) to get (even) better results.

The dissertation has shown that the dependency of electricity generation on constant water supply has to be comprehensively considered in holistic governance approaches to sustainably guarantee energy-water security. The dissertation's overarching character, that goes from the macro over the meso to the micro level of governance and management action, demands from all the actors of the Anthropocene - politicians, companies, citizens, stakeholders of all kind - greater attention if they want to continue its thriving in a stable *and* secure *and* sustainable manner. Governance on various levels needs to unveil energy-water challenges, adapt their infrastructure planning and induce a holistic thinking in energy-water management.

If not, "hidden" dependency processes like reservoir sedimentation will soon reveal on a grand scale that the energy-water infrastructures like hydro power reservoirs are not as stable, secure and sustainable as they might appear - and that they indeed are not forever if left managed without a security and sustainability mindset. Water-dependent electricity generation is indeed quite fragile in the case where its inherent challenges are left untouched. The main aim of this dissertation was to touch this delicate matter in a thorough, but not exhaustive, manner and that it contributed to a more sustainable and secure future in the spirit of Grey and Sadoff (2007) and World Commission on Environment and Development (1987).

DECLARATION OF ORIGINALITY

I declare that this research is my own work except where there is clear acknowledgment and reference to the work of others. This research does not contain material that has already been used to any substantial extent for a comparable purpose.

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CHAPTER

8 SUPPLEMENTARY MATERIAL

8.1 Supplementary Material to Chapter 3

Table S1: Participant distribution during the III. WANDEL Morocco Workshop

	Q1 (Pre-Activity)	Q2 (Post-Activity)	Q3 (Post-Activity)	Q4 (S8)
Administration	6	6	6	5
Civil	10	8	8	8
Agriculture	1	3	3	3
Research	2	1	1	1
Sum	19	18	18	17

8.2 Supplementary Material to Chapter 2

Various materials are contained herein that did not find their way into the main document. However, they are important for fully retracing the composition of some sub-indicators, which is why they are displayed on the following pages.

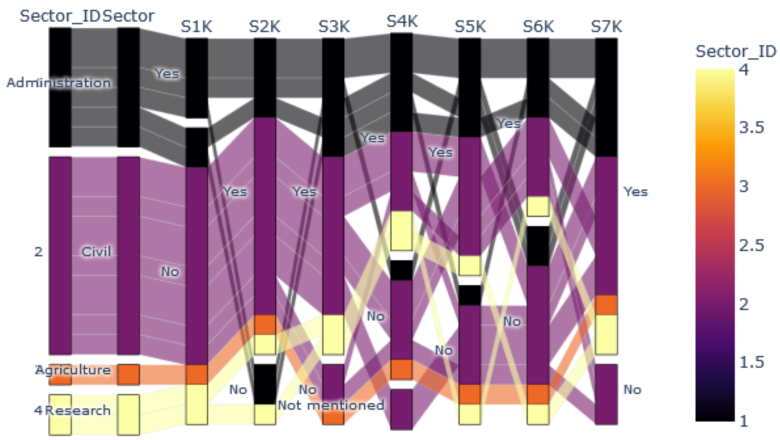


Figure S1: Strategies known to the participants prior to the workshop

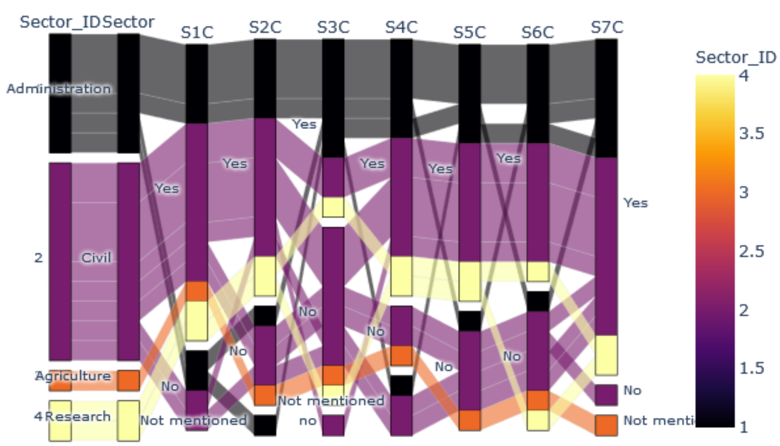


Figure S2: Pre-workshop confidence that a strategy would have effect in the MDV

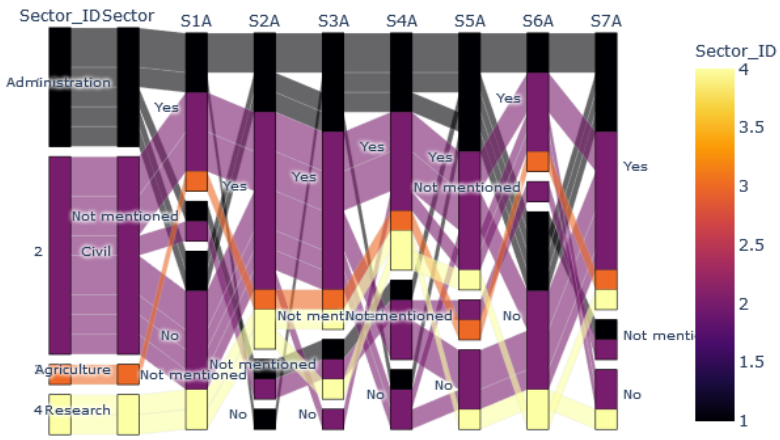


Figure S3: Assumed pre-workshop application of the strategy in the MDV

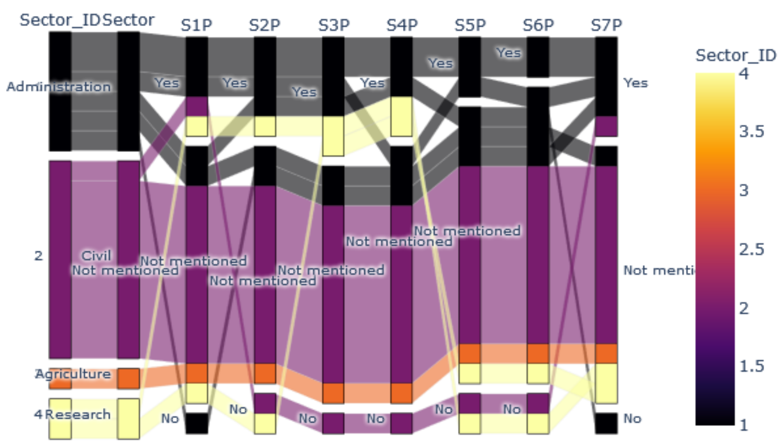


Figure S4: Pre-workshop estimation of the strategies' practical effect, if application already assumed

Table S2: Full list of emergent policies/organisations/programs

Policy/Organisation/Program	Translatio/Explanation	Strategies mentioned for	Mentioned by
INDH	National Human Development Initiative	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
ABH	Basin Agencies	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
PMV	Green Morocco Plan	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
GCT	Grouping of of territorial communities	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
CML	National Committee for the Control of Leishmaniasis	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
FDT	Draa Tafilaht Foundation for Researchers and Experts	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
FDA	Agricultural Development Fonds	s. Figure Chapter 4.1.	s. Figure Chapter 4.1.
Conventions d'Agriculture Goutte-à-Goutte/Arrosage	National Drinking Water Supply and Irrigation Programme	S2,S5	Research, Administration
Transfer d'eau entre basins	Yet unrealized plan to build a canal to transfer water from the region of Fes Mekness to the regions of Marrakes Safi and Souss Massa	S3, S3	Administration
Conseil provincial Zagora	Zagora Provincial Council	S3, S5	Research, Administration
Périmetre Unique Gestion des Déchets	Waste Management Organisation	S3, S4	Administration
CNE	Morrocan National Water Council (Conseil national de l'eau)	S5, S5	Administration
AUEA	Agricultural Water Users Associations	S7, S7	Administration
FAO	The UN's Food and Agriculture Organisation	S1	Administration
DGCL	Directorate General for Local Authorities	S1	Administration
RAZDED	Network of Zagora Associations for Development and Democracy	S7	Civil
AI	Agence d'irrigation Draa Tafilalt	S7	Civil
CTB	Belgian Technical Cooperation	S4	Research
GIZ	The German Corporation for International Cooperation GmbH	S4	Administration
Chambre d'agriculture	Chamber of Agriculture of the region Souss Massa	S4	Civil
Dar Alomouair	Semi-public institutions, project to support households and farmers	S4	Administration
Dar El Fatat	Semi-public institutions, project to support households and farmers	S4	Administration
Comité de la lutte contre la violoence contre la femme et les infants	Committee to combat violence against women and children	S5	Civil
Ministère de L'Equipment	Ministry of Equipment, Transport and Logistics	S6	Administration
Intensification de palmier dattier	Sub-Project within the PMV	S2	Administration
Contrat de nappe	region of Souss Massa, called the contrat nappe, to the other regions in Morocco; part of the ABH	S3	Administration
Convention entre ABH/ORMVA	Convention between the Regional Office of Agricultural Cultivation (ORMVA) and the ABH	S3	Administration
Ceinture Verte Zagora	Project Green Belt Zagora by the High Commission for Water and Forestry	S3	Administration
Chambre Froides e Puits Communs	Cooling rooms, common wells	S4	Civil

8.2.1 Inter-Sectoral Competition

A graph displaying the inter-sectoral competition (ICI) distribution is displayed in Figure S10.

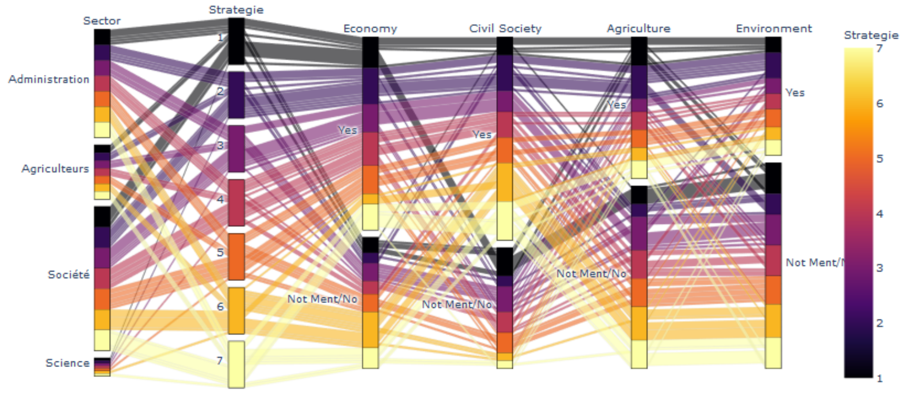


Figure S5: Advantages for certain sectors in case of strategy application perceived by the participants

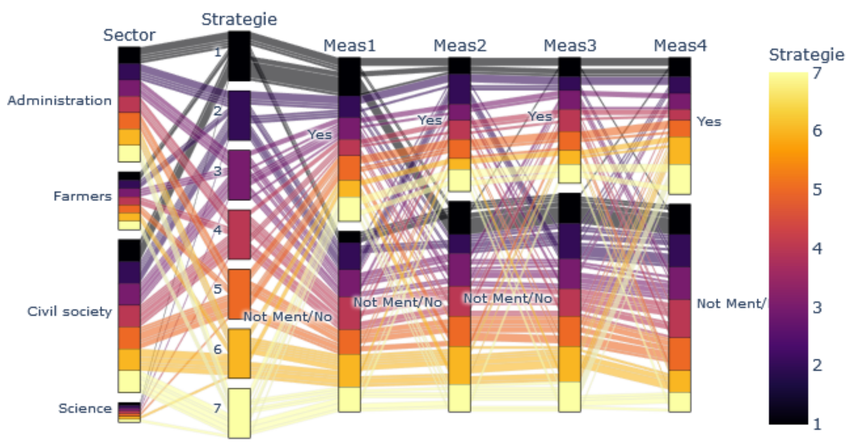


Figure S6: Advantages for certain measure implementation in case of strategy application perceived by the participants

8.2.2 Water Temperature Variation

The risk classification of the peak temperature events (PTEs) is displayed in Figure S3.

The risk classification of the long-term temperature change (LTC) is displayed in Figure S4.

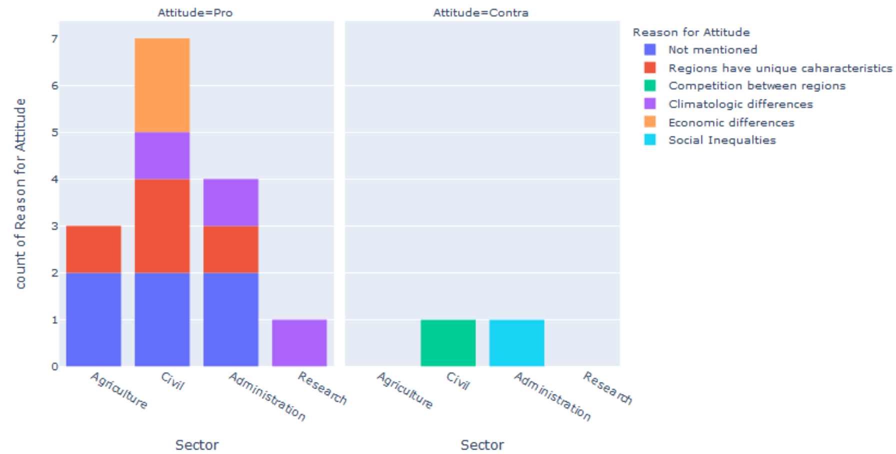


Figure S7: Participants' preference of water withdrawal regionalization

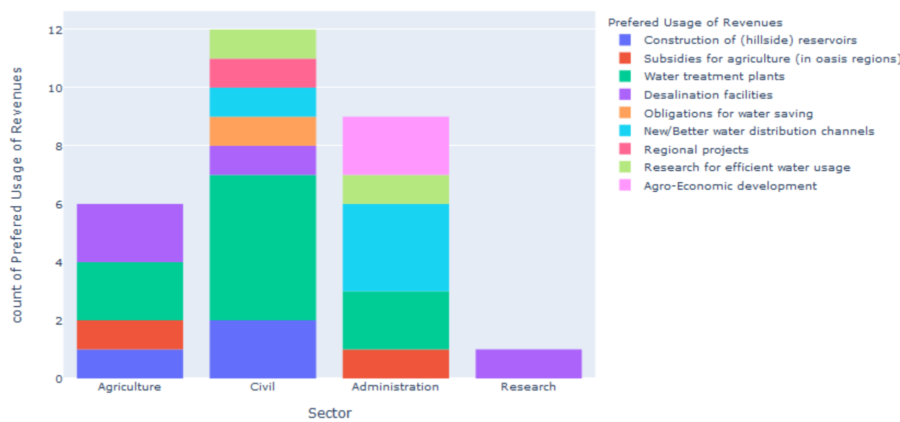


Figure S8: Participants preferred usage of the hypothetical water withdrawal charges

Table S3: The PTE Rating

Rating	PTE Rating
5	PTE > 125%
4	125% > PTE > 115%
3	115% > PTE > 105%
2	105% > PTE > 102.5%
1	PTE < 102.5%

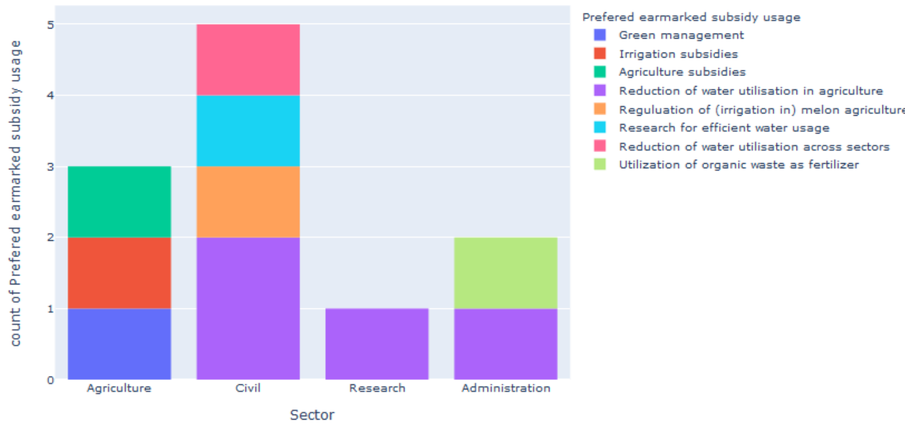


Figure S9: Participants preferred usage of the hypothetical water withdrawal if utilized as earmarked subsidies

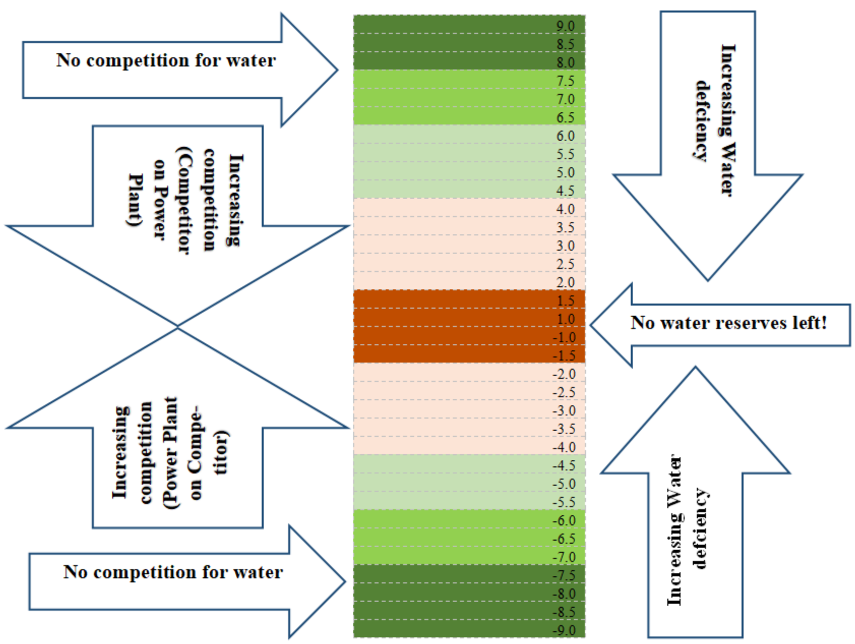


Figure S10: The functionality of the ICI

8.2.3 Drought and Flood Vulnerability

The risk classification of the drought and flood sub-indicators consists of three units, namely, the standardized precipitation-evaporation index (Vicente-Serrano

Table S4: The LTC Rating

Rating	LTC Rating
5	LTC > 125%
4	125% > LTC > 115%
3	115% > LTC > 105%
2	105% > LTC > 102.5%
1	LTC < 102.5%

et al., 2010; Tirivarombo et al., 2018), gravity recovery and climate experiment - drought severity index (Zhao et al., 2017)and the groundwater vulnerability index (Federal Institute for Geosciences and Natural Resources Germany, 2015). The main article describes IPV's aggregation. The three units are individually classified according to Tables S5, S6 and S7.

Table S5: The SPEI Rating

Rating	SPEI Rating
5	SPEI > 0.25
4	0.25 > SPEI > 0.15
3	0.15 > SPEI > 0.075
2	0.075 > SPEI > 0.025
1	SPEI < 0.025

Table S6: The GRACE-DSI Rating

Rating	GRACE-DSI Rating
5	GRACE-DSI > 0.25
4	0.25 > GRACE-DSI > 0.15
3	0.15 > GRACE-DSI > 0.075
2	0.075 > GRACE-DSI > 0.025
1	GRACE-DSI < 0.025

Table S7: The GVI Rating based on the Total Vulnerability Range (TVR) (Federal Institute for Geosciences and Natural Resources Germany, 2015)

Rating	GVI Rating
5	TVRf > 60 and TVRd > 60
4	TVRf > 60 and 60 > TVRd > 40 OR TVRd > 60 and 60 > TVRf > 40
3	60 > TVRf > 40 and 60 > TVRd > 40
2	60 > TVRf > 40 and 40 > TVRd OR 60 > TVRd > 40 and 40 > TVRf
1	40 > TVRf and 40 > TVRd

8.2.4 Energy-Water Legislation

The questionnaires that were/are to be utilized for the semi-guided expert interviews are displayed in Figures S11, S12 and S13. In a subsequent re-evaluation of the interview, the questions were scored. This is done in case the interviewees refrained from doing so themselves (as they, e.g., favoured just the oral interview).

The questionnaires'evaluation follows the "weakest link"-assumption, i.e., that the legal system already suffers tremendously if one score is weak. A weak score cannot be cancelled out by a positive score (within a question). Thus, in each question, the weakest (or, in this case, highest) score is considered.

The questions are then aggregated, and a simple arithmetical average is formed. Questions that do not follow the 1-5 scoring pattern are spared.

8.2.5 Energy-Water Administration

The questionnaires that were/are to be utilized for the semi-guided expert interviews are displayed in Figures S14 and S15. In a subsequent re-evaluation of the interview, the questions were scored. This is done in case the interviewees refrained from doing so themselves (as they, e.g., favoured just the oral interview).

The questionnaires'evaluation follows the "weakest link"-assumption, i.e., that the administrative system already suffers tremendously if one score is weak. A weak score cannot be cancelled out by a positive score (within a question). Thus, in each question, the weakest (or, in this case, highest) score is considered.

The questions are then aggregated, and a simple arithmetical average is formed. Questions that do not follow the 1-5 scoring pattern are spared.

Water

Legal weaknesses caused by internal flaws regarding the quality (temperature, chemical properties, salinity etc.) of surface or groundwater. Flaws are e.g.: Superficiality, ambiguity, incompleteness. *

'5'stands for weak laws full of flaws, '1' reflects vast set quality aspects that gets covered thoroughly on a high level.

	complete in-depth unambiguous 1	2	3	4	incomplete superficial ambiguous 5	Weighting --	-	+	++
Municipal/County	○	○	○	○	○	○	○	○	○
State/Region	○	○	○	○	○	○	○	○	○
Interstate/Interregional	○	○	○	○	○	○	○	○	○
National	○	○	○	○	○	○	○	○	○

Legal weaknesses caused by internal flaws regarding quantity and distribution (to residents/industry/agriculture etc.) of surface or groundwater. Flaws are e.g.: Superficiality, ambiguity, incompleteness or one-sidedness. *

'5' stands for the most one-sided, incomplete or intransparant law, '1' reflects a thorough and vast set of aspects that gets covered completely, fair and transparantly.

	complete fair transparant 1	2	3	4	incomplete one-sided intransparant 5	Weighting --	-	+	++
Municipal/County	○	○	○	○	○	○	○	○	○
State/Region	○	○	○	○	○	○	○	○	○
Interstate/Interregional	○	○	○	○	○	○	○	○	○
National	○	○	○	○	○	○	○	○	○

Energy

Legal weaknesses caused by internal flaws regarding quantity and distribution (to residents/industry/agriculture etc.) of energy. Flaws are e.g.: Superficiality, ambiguity, incompleteness or one-sidedness. *

'5' stands for the most one-sided, incomplete or intransparant law, '1' reflects a thorough and vast set of aspects that gets covered completely, fair and transparantly.

	complete fair transparant 1	2	3	4	incomplete one-sided intransparant 5	Weighting --	-	+	++
Municipal/County	○	○	○	○	○	○	○	○	○
State/Region	○	○	○	○	○	○	○	○	○
Interstate/Interregional	○	○	○	○	○	○	○	○	○
National	○	○	○	○	○	○	○	○	○

Legal weaknesses caused by internal flaws regarding sustainability (incentives for renewables, decentralization, reduction of emissions etc.) of energy resources. Flaws are e.g.: Superficiality, ambiguity, incompleteness. *

'5' stands for the most superficial, incomplete and ambiguous law, '1' reflects a thorough and vast set of aspects that gets covered in-depth, completely and unambiguously.

	complete in-depth unambiguous 1	2	3	4	incomplete superficial ambiguous 5	Weighting --	-	+	++
Municipal/County	○	○	○	○	○	○	○	○	○
State/Region	○	○	○	○	○	○	○	○	○
Interstate/Interregional	○	○	○	○	○	○	○	○	○
National	○	○	○	○	○	○	○	○	○

Figure S11: Guidance questionnaire for semi-guided expert interviews

Water-Energy

Is there an interrelationship between water legislation and legislation for energy generation? *

Choose the most fitting option.

- ◯ There is none.
- ◯ Water and energy laws have only interrelations in special cases.
- ◯ The codes of legislation are completely the same.

Do stakeholders/lawyers have problems to work with this law organization for water supply and energy generation due to complexity, intransparancy or opaqueness? *

'5' stands for an administrative structure that is opaque, overly complex and very hard to work with, '1' reflects a legal organization that is easy to work with to produce swift and clear desicions.

	Not complex Transparent Easy to work with 1	2	3	4	Complex Intransparent Hard to work with 5	Weighting --	-	+	++
The legal structure is...	◯	◯	◯	◯	◯	◯	◯	◯	◯

Are there different law codes that oppose, contradict or annul each other in a way, that water or energy security in a sector gets massively reduced? How strong is the effect of this legal confusion? *

'5' reflects an administrative contradiction that has tremendous negative consequences, '1' stands for almost no negative influence at all.

	No contradiction 1	2	3	4	Massive contradiction 5	Weighting --	-	+	++
Internal contradiction (water)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Internal contradiction (energy)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Contradiction between water and energy law codes	◯	◯	◯	◯	◯	◯	◯	◯	◯

Are there special laws that ignore, consider or favor "environmental" needs for water during the respective phase of the life cycle of a power plant? *

'5' stands for a complete ignorance, '3' depicts fair consideration, '1' favors the water needs of the environment.

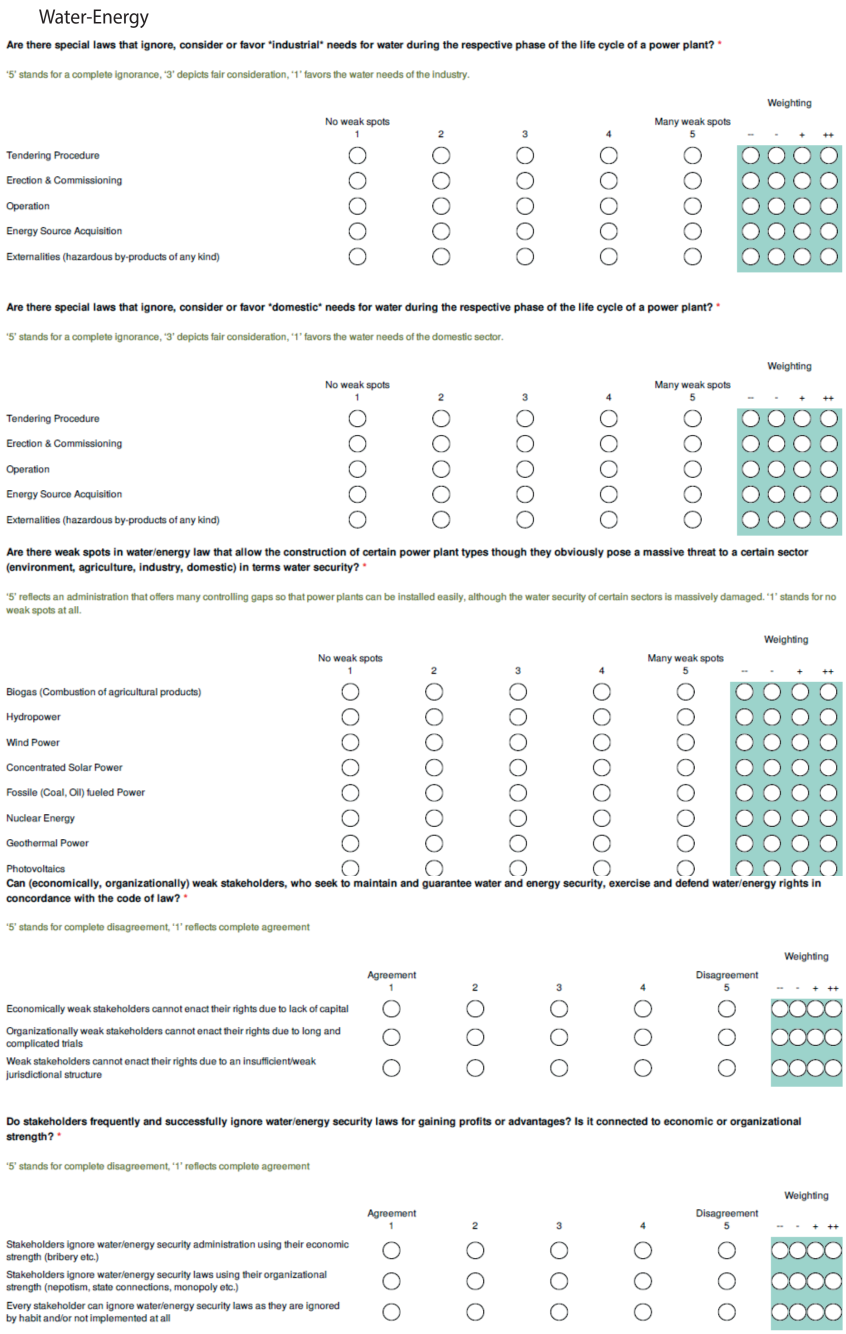
	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Tendering Procedure	◯	◯	◯	◯	◯	◯	◯	◯	◯
Erection & Commissioning	◯	◯	◯	◯	◯	◯	◯	◯	◯
Operation	◯	◯	◯	◯	◯	◯	◯	◯	◯
Energy Source Acquisition	◯	◯	◯	◯	◯	◯	◯	◯	◯
Externalities (hazardous by-products of any kind)	◯	◯	◯	◯	◯	◯	◯	◯	◯

Are there special laws that ignore, consider or favor "agricultural" needs for water during the respective phase of the life cycle of a power plant? *

'5' stands for a complete ignorance, '3' depicts fair consideration, '1' favors the water needs of the agriculture.

	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Tendering Procedure	◯	◯	◯	◯	◯	◯	◯	◯	◯
Erection & Commissioning	◯	◯	◯	◯	◯	◯	◯	◯	◯
Operation	◯	◯	◯	◯	◯	◯	◯	◯	◯
Energy Source Acquisition	◯	◯	◯	◯	◯	◯	◯	◯	◯
Externalities (hazardous by-products of any kind)	◯	◯	◯	◯	◯	◯	◯	◯	◯

Figure S12: Guidance questionnaire for semi-guided expert interviews



Water-Energy

Are there special laws that ignore, consider or favor *industrial* needs for water during the respective phase of the life cycle of a power plant? *

'5' stands for a complete ignorance, '3' depicts fair consideration, '1' favors the water needs of the industry.

	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Tendering Procedure									
Erection & Commissioning									
Operation									
Energy Source Acquisition									
Externalities (hazardous by-products of any kind)									

Are there special laws that ignore, consider or favor *domestic* needs for water during the respective phase of the life cycle of a power plant? *

'5' stands for a complete ignorance, '3' depicts fair consideration, '1' favors the water needs of the domestic sector.

	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Tendering Procedure									
Erection & Commissioning									
Operation									
Energy Source Acquisition									
Externalities (hazardous by-products of any kind)									

Are there weak spots in water/energy law that allow the construction of certain power plant types though they obviously pose a massive threat to a certain sector (environment, agriculture, industry, domestic) in terms water security? *

'5' reflects an administration that offers many controlling gaps so that power plants can be installed easily, although the water security of certain sectors is massively damaged. '1' stands for no weak spots at all.

	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Biogas (Combustion of agricultural products)									
Hydropower									
Wind Power									
Concentrated Solar Power									
Fossile (Coal, Oil) fueled Power									
Nuclear Energy									
Geothermal Power									
Photovoltaics									

Can (economically, organizationally) weak stakeholders, who seek to maintain and guarantee water and energy security, exercise and defend water/energy rights in concordance with the code of law? *

'5' stands for complete disagreement, '1' reflects complete agreement

	Agreement 1	2	3	4	Disagreement 5	Weighting --	-	+	++
Economically weak stakeholders cannot enact their rights due to lack of capital									
Organizationally weak stakeholders cannot enact their rights due to long and complicated trials									
Weak stakeholders cannot enact their rights due to an insufficient/weak jurisdictional structure									

Do stakeholders frequently and successfully ignore water/energy security laws for gaining profits or advantages? Is it connected to economic or organizational strength? *

'5' stands for complete disagreement, '1' reflects complete agreement

	Agreement 1	2	3	4	Disagreement 5	Weighting --	-	+	++
Stakeholders ignore water/energy security administration using their economic strength (bribery etc.)									
Stakeholders ignore water/energy security laws using their organizational strength (nepotism, state connections, monopoly etc.)									
Every stakeholder can ignore water/energy security laws as they are ignored by habit and/or not implemented at all									

Figure S13: Guidance questionnaire for semi-guided expert interviews

Water

Organizational competence of the water related administration *

'5' stands for the most opague, impotent and contradictive administration, '1' reflects a capable, potent and clear organizational structure.

	clear potent capable 1	2	3	4	opague impotent contradictive 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Employee competence of the water related administration *

'5' stands for the most uneducated, impotent and quantitative unsufficient administrative workforce, '1' reflects a capable, potent and quantitative sufficient staff.

	capable potent sufficient staff 1	2	3	4	uneducated impotent too small staff 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Indepency of the water related administration from entities with interests other than the public good (e.g. capital profit, individual advantages, corruption) *

'5' stands for a stongly biased, influenced and dependent administration, '1' reflects an independent, unbiased and task focused organization.

	task focused unbiased independent 1	2	3	4	influenced biased dependent 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Energy

Organizational competence of the energy related administration *

'5' stands for the most opague, impotent and contradictive administration, '1' reflects a capable, potent and clear organizational structure.

	clear potent capable 1	2	3	4	opague impotent contradictive 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Employee competence of the energy related administration *

'5' stands for the most uneducated, impotent and quantitative unsufficient administrative workforce, '1' reflects a capable, potent and quantitative sufficient staff.

	capable potent sufficient staff 1	2	3	4	uneducated impotent too small staff 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Indepency of the energy related administration from entities with interests other than the public good (e.g. capital profit, individual advantages, corruption) *

'5' stands for a stongly biased, influenced and dependent administration, '1' reflects an independent, unbiased and task focused organization.

	task focused unbiased independent 1	2	3	4	influenced biased dependent 5	Weighting --	-	+	++
Municipal/County									
State/Region									
Interstate/Interregional									
National									

Figure S14: Guidance questionnaire for semi-guided expert interviews

Water-Energy

Is there an interrelationship between water administration and the administration for energy generation in the region? *

Choose the most fitting option.

- There is none.
- Administrations for water and energy only have interrelation in special cases.
- Energy and water administration belong to the same unit and are stongly intertwined..

Do employees or stakeholders have problems to work in this administrative context of water supply and energy generation due to complexity, intransparancy or opaqueness? *

'5' stands for an administrative structure that is opaque, overly complex and very hard to work with, '1' reflects a legal organization that is easy to work with to produce swift and clear desicions.

	Not complex Transparent Easy to work with 1	2	3	4	Complex Intransparent Hard to work with 5	Weighting --	-	+	++
The administrative cooperation between water and energy issues is...									

Are there different administrative entities that oppose, contradict or annul each other in a way, that water or energy security in a sector is massively reduced? How strong is the effect of this administrative contradiction? *

'5' reflects an administrative contradiction that has tremendous negative consequences, '1' stands for almost no negative influence at all.

	No contradiction 1	2	3	4	Massive contradiction 5	Weighting --	-	+	++
Internal contradiction (water)									
Internal contradiction (energy)									
Contradiction between water and energy entities									

Does the administrative water control offer weak spots that allow the construction of certain power plant types though they obviously pose a massive threat to a certain sector (environment, agriculture, industry, domestic) in terms water security? *

'5' reflects an administration that offers many controlling gaps so that power plants can be installed easily, although the water security of certain sectors is massively damaged. '1' stands for no weak spots at all.

	No weak spots 1	2	3	4	Many weak spots 5	Weighting --	-	+	++
Biogas (Combustion of agricultural products)									
Hydropower									
Wind Power									
Concentrated Solar Power									
Fossile (Coal, Oil) fueled Power									
Nuclear Energy									
Geothermal Power									
Photovoltaics									

Can (economically, organizationally) weak stakeholders, who seek to maintain and guarantee water and energy security, exercise and defend water and/or energy security rights in the current administrative system? *

'5' stands for complete disagreement, '1' reflects complete agreement

	Agreement 1	2	3	4	Disagreement 5	Weighting --	-	+	++
Economically weak stakeholders cannot enact their rights due to lack of capital									
Organizationally weak stakeholders cannot enact their rights due to overly complicated administrative processes									
Weak stakeholders cannot enact their rights due to an unsufficient/weak administrative structure									

Do stakeholders frequently and successfully ignore administrative structures for water/energy security in order to gain profits or advantages? Is it connected to economic or organizational strength? *

'5' stands for complete disagreement, '1' reflects complete agreement

	Agreement 1	2	3	4	Disagreement 5	Weighting --	-	+	++
Stakeholders ignore water/energy security administration using their economic strength (bribery etc.)									
Stakeholders ignore water/energy security administration using their organizational strength (nepotism, state connections, monopoly etc.)									
Every stakeholder can ignore water/energy security administration as it is generally weak									

Figure S15: Guidance questionnaire for semi-guided expert interviews