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# Problems Concerning Ancient Water Management in the Mediterranean

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# Problems Concerning Ancient Water Management in the Mediterranean

Throughout history, societies have performed water management to provide themselves with water for several purposes. Here, three main entities of water management can be distinguished, which are: water availability, water technology and social organization. These three entities with their specifications and some examples will be presented in this study. The study categorizes and classifies some basic terms of water management, with a focus on the antique Mediterranean. For a holistic analysis of water management we suggest the utilization of an integrated approach called social ecology.

Water availability; water technology; social organization; social ecology.

## 1 Introduction

The management of water is an indispensible requirement for humans and societies. The multi-faceted nature of water itself, its spatially and temporally varying availability, the applied water technologies and their impact on societies make it a complex study subject. In this sense, the following paragraphs try not only to categorize and classify some basic terms of water management but also show how to avoid certain gaps and misinterpretations. We hope that it could function as guidance on how to approach water management issues in a more holistic and contextualized manner.

Numerous studies about water management exist, but, frequently, they do not incorporate all of the entities, functions and problems related to the issue. Instead, studies often approach the subject by focusing on (i) the natural settings, (ii) the technical properties or (iii) the social settings. These three main approaches are tentatively classified as the (i) hydro, (ii) techno and (iii) social approach, respectively (examples and references in chapters 4 and 5).

Thus, this contribution is also intended to provide a way of differentiating among water management studies and outline water management as a holistic topic that needs integrative approaches. Though our examples focus on the Mediterranean regions in antiquity, we intend to show the spatial and temporal invariance of water management problems.

However, the Mediterranean regions are special for the study of water management, because here one is confronted with a rich history and a 'bewildering variety' of water management issues closely related to the seasonality of the Mediterranean climate which necessitates water management strategies for many human activities.[1] These strategies consist essentially of agricultural efforts, which have a long history in the Mediterranean regions. Good examples for this are traditional methods of irrigation and measures that harvest, augment, store or provide water and sediments for agricultural fields.

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[1] Horden and Purcell 2000.

## 2 Water management – its definition and main entities

"Water management is the interruption and redirection of the natural movement or collection of water by society".[2] This definition covers all important aspects of water management, including the natural movement of water (i.e. the hydrological cycle), the redirection and collection of water (i.e. the application of certain strategies or technologies to alter or redirect the natural flow) and the societies who developed special governance structures to regulate the resource water. In this paper, we will focus on these three entities, and generalize these rather process-oriented terms by using the terms water availability, water technology and social organization (Fig. 1). All three entities will be described in detail in the second part of this chapter (see 4.1–4.3).

Fig. 1 | The three main entities of water management.

To evaluate water management systems, all three entities are of relevance, but, at the same time, each entity offers its own complexity and there are hardly any examples in scientific literature in which all three entities are considered comprehensively or in an integrated manner. Thus, studies about water management frequently do not address all three entities, but focus instead on specific problems or issues, both in order to reduce the complexity and to enable specific case studies. In this paper, studies that focus on water availability are subsumed under the term *hydro approach,* studies focusing on *water technology* under the term *techno approach* and studies focusing on *social organization* under the term *social approach* (Fig. 2).

Water management incorporates a very broad and complex set of factors, actors and processes that typically resists straightforward analysis or comparison. An example for this is the long-discussed question of whether early state-building societies such as those in Egypt, Mesopotamia, South Asia, East Asia, Central or South America emerged as a consequence of a need for a comprehensive water management (often called "large-scale irrigation"[3]) or whether the societies gradually developed that need. Here, problems occur with deterministic concepts like the well-known Wittfogel hypothesis (chapter 4.3).

For the investigation of human-nature interactions, including the access and exploitation of natural resources like water, various problems exist regarding how to integrate and compare the different components. For that reason, we will now present a concept of 'social ecology' that is adapted to water management. This approach is an attempt to overcome deterministic, dichotomous or non-integrated dualistic views, but allows us to tentatively select processes and compare or even quantify them (chapter 3).We pursue the objective that many problems, e.g. of temporal and social nature, can be treated with this theory, as water management is not specific for a certain time or social entity, but the consequence of a process incorporating the following: a specific water demand, the technical realizations to reach this demand, the natural availability of water itself and the social frame to govern these processes.

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[2] Scarborough 1991, 1.

[3] Harrower 2009.

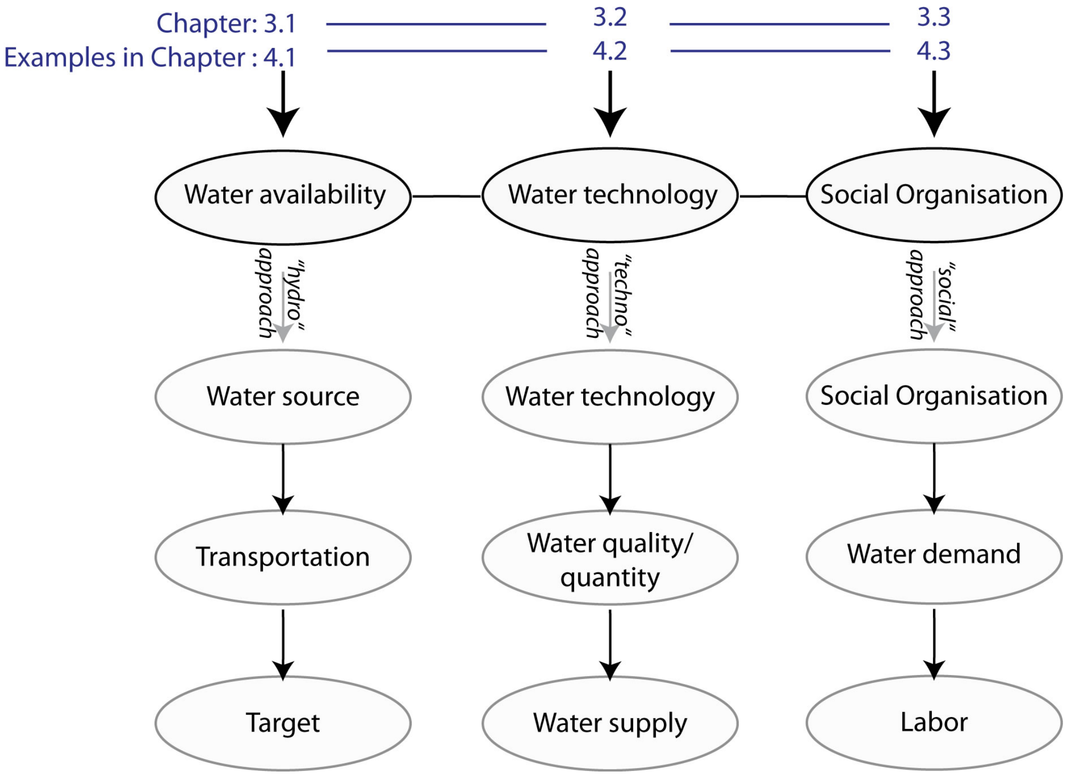

Fig. 2 | The entities and approaches with their respective paragraphs and chapters in which they are presented.

## 2.1 Theoretical considerations on how to approach issues regarding the integration of humans in nature and the relation of humans and nature

How does water management – once it is integrated into a society – change that society? Do water management techniques lead to comparable spatial organizations of settlements and their related functions? In order to answer such questions, which are related to technical knowledge as well as to knowledge about the environment, we need a holistic model of society–nature interactions integrating the cultural and natural systems. On that basis, we will be able to identify and analyze the different complex relations between environmental conditions, societal demands and cultural knowledge.

## 2.2 A holistic model of society-nature interaction

There are many different theories that aim to integrate and understand the complex interplay of human and environment, culture and nature.[4] Most of them share a dichotomous or at least not-integrated view of nature and culture. However, as Latour in particular has pointed out:[5] we are not able to distinguish *us* from the rest of the world. The world as it can be discovered by us is constituted of hybrid elements that share material and immaterial characteristics. In this reading, we, as humans, can also be seen as hybrids: as living beings, we are part of the material world that follows physical laws which force us

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[4] For a historical perspective until the 18th century, see Glacken 1967; an overview of younger approaches give Jeans 1974; Norton 2000.

[5] Latour 2008.

to drink, eat and reproduce in order to not become extinct. We are, however, also part of an immaterial world of consciousness and thought, of societal structures and culture that guides our behavior and decisions – and that can be materially represented by tools, art or writings.

This dualistic view is integrated into the social-ecological concept of societal metabolism[6] under which society is understood as the structural coupling of a cultural system with biophysical elements, i.e. the population.[7] This is a systemic approach, following the ideas of the theory of second-order systems,[8] centering on autopoietic systems, i.e. systems that are self-referential and operatively closed, which reproduce themselves and maintain a border with their environment. Under the social-ecological concept, the direct connection between human society and the material world is called metabolism.[9] Hence, a measurement of the fluxes between a population and the material world allows the assessment of its metabolic state or socio-ecological regime.[10] But these fluxes are intrinsically dynamic, not least because humans have the ability to change their environment. This is considered in the approach of societal metabolism as the colonization of nature:[11] an intentional and sustained alteration of natural processes that is intended to change a society's state.[12] This is based on Marx' definition of *labor*, which considers the feedback mechanisms between existing environmental conditions, human alteration of them and the resulting effects on human beings themselves.[13]

We can approach the immaterial side of this dualistic view by refering to Luhmann,[14] who proposes a systemic view of society constituted by recursive communication. Communication is the direct connection between human population and culture, thus the immaterial counterpart of the metabolism.[15] In such a society, external influences of nature are excluded.[16] Accordingly, it is difficult to explain, using Luhmann's concept, how social systems are able to modify nature.[17] Nevertheless, a connection is indispensable. It can be found in human beings themselves, as hybrids of a culturally influenced consciousness and a body that is controlled by the laws of nature. Thus, social systems in general and society in particular are regarded as structurally coupled between specific biophysical structures and a social system in Luhmann's reading.[18]

The approach of social ecology is applied mainly to modern and historical questions focusing on sustainability issues or describing the general picture of societal development and transitions throughout history.[19] This is clearly related to the large amount of data that is necessary to analyze the different flows of stocks and energy within the coupled system of human and environment interactions and which is only available for more

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[6] Sieferle 1997; in general Fischer-Kowalski, Haberl, et al. 1997.

[7] Fischer-Kowalski and Erb 2006, 40; Fischer-Kowalski, Mayer, and Schaffartzik 2011, 98.

[8] See Foerster 2003.

[9] Fischer-Kowalski, Mayer, and Schaffartzik 2011, 101.

[10] E.g. Krausmann, Schandl, and Sieferle 2008.

[11] Fischer-Kowalski, Mayer, and Schaffartzik 2011, 99.

[12] Weisz et al. 2001, 123.

[13] Marx and Engels 1906, 197–198: "Labour is, in the first place, a process in which both man and Nature participate, and in which man of his own accord starts, regulates, and controls the material re-actions between himself and Nature. He opposes himself to Nature as one of her own forces, setting in motion arms and legs, head and hands, the natural forces of his body, in order to appropriate Natures productions in a form adapted to his own wants. By thus acting on the external world and changing it, he at the same time changes his own nature."

[14] Luhmann 2012.

[15] Fischer-Kowalski, Mayer, and Schaffartzik 2011, 101.

[16] E. g. Luhmann 2012, 60–61.

[17] Fischer-Kowalski, Mayer, and Schaffartzik 2011, 99.

[18] Fischer-Kowalski, Mayer, and Schaffartzik 2011, 100.

[19] E. g. Weisz et al. 2001; Schandl et al. 2009; Haberl et al. 2004; Sieferle et al. 2006; Fischer-Kowalski, Krausmann, and Smetschka 2004.

recent periods or in a coarser resolution – not to mention the difficulty of interpreting and *quantifying* social fluxes, i.e. communication.

Given the nature of archaeological data,[20] we use the ideas of social ecology only as a heuristic to help us explain and understand (a) how the relationship between human beings and environment can be characterized in general and (b) how this relationship is characterized particularly in terms of water management.

In order to achieve this goal, we have simplified the model of social ecology to match it to an archaeological context (Fig. 3). The center is made up of artifacts, carrying the major information on the prehistoric world. Artifacts are, like humans, hybrid elements, because they incorporate elements both of the immaterial world, for instance thoughts, cultural values and knowledge, as well as of the material world, for instance the characteristics of the raw material.[21] Examples for artifacts are pottery, houses, settlements, streets and domestic animals and plants, and, in the context of water management, terraces, wells, qanats, canals or dams. These artifacts illustrate a specific connection between human beings and their surroundings, i.e. their landscape. Grounding our model on artifacts leaves no space for an unaffected nature. Everything that we discover has been humanized. As we shape our landscape, the material surroundings via the means of *labor*, so we shape ourselves, since doing so will change the metabolism.[22]

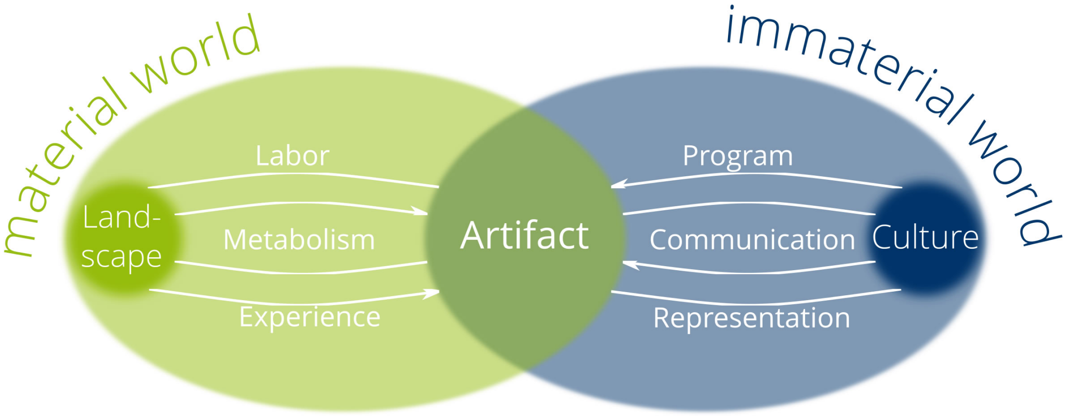

Fig. 3 | Concept of human-nature interactions.

We can apply our model to questions regarding water management, illustrated for instance by aqueducts (Fig. 4): We do not know when the first human being experienced its ability to direct water along a slope by means of constructions, but this experience and its representation within cultural knowledge shows the necessity of a cultural program that aims to improve living conditions at a certain location through an intervention in the present metabolism. This has to be done by using the organized labor of a group of people within the landscape to build an artifact that changes the metabolism of the urban, but also of the rural population. Construction costs may have a negative impact on the metabolism during construction. Once the aqueduct is built, the society has to organize continuous communication in order to spread the knowledge of how to maintain it, in order to preserve the new metabolic level. This is also part of the new level of metabolism.

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[20] E. g. Renfrew and Bahn 2012, 49–50.

[21] For an illustrative example, see Latour 1991.

[22] Godelier 1986, 4–5.

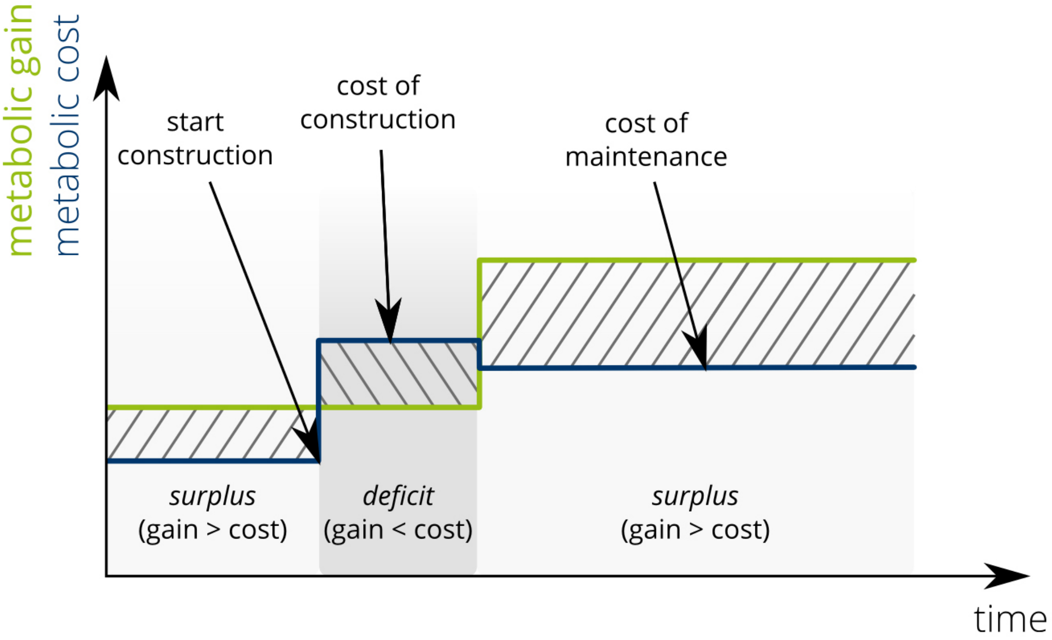

Fig. 4 | The change of metabolic cost and gain when a new artifact is built.

# 3 The three entities of water management

We emphasize that the following paragraphs are not arranged in a hierarchical order. Moreover, we do not claim that this generic classification is complete or exclusive.

## 3.1 Water availability

Water availability is the balance of naturally available water that derives from the hydrological cycle.[23] For this study, only the three main water sources: precipitation, surface water and groundwater, and their typical problems are considered.

### 3.1.1 Water sources

Basically the only source of fresh water is *precipitation*.[24] Considering the precipitation that falls over the continents, it can (i) be used directly for rain-fed agriculture or rooftop harvesting, or it can (ii) accumulate and lead to *surface water* (runoff) or it can (iii) infiltrate and become *groundwater*.[25]

### 3.1.2 Precipitation

Precipitation or rainfall can be described in terms of its character (quantity, duration, intensity, aggregate state), its patterns (variance, variability, trends, frequency and spatial

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[23] Oki and Kanae 2006, fig. 4.

[24] The exceptions are the direct usage of humidity (e.g. fog or dew harvesting) and salt- or seawater desalinization.

[25] For a quantitative analysis, one would have to take more variables and processes into account, like: evaporation and evapotranspiration, change in storage (of the soil and the bedrock), and is referred to the water balance equations or the hydrological cycle: e.g. Oki and Kanae 2006 .

distribution) or its peculiarities (range between extreme or anomalous values or other indices).[26]

The most common tool to approach precipitation is to use averaged values of 30-year climate periods. The use, however, of data as condensed as that available in climate charts, for example, poses several problems. These problems concern either the *temporal* resolution, e.g. the application of aggregated monthly data on specific short-term conditions, or the *spatial* resolution, e.g. the application of data from a weather station that is not representative for a specific study site.[27]

A good overview approximation for Mediterranean climates seems to be that they emphasize either (i) annual vegetation with wet winters and summer droughts or (ii) evergreen sclerophylls with relatively short dry spells and (iii) monthly average temperatures of $> 0°C$; while annual precipitation ranges from 250 to 400 mm ($325 \pm 75$ mm).[28] It has to be emphasized that, over longer periods of time, averaged data of this kind is problematic. Short term events such as droughts (water deficits) or flooding (water excess) are characteristic for Mediterranean regions and are not reflected in such averaged data. The functioning of any water management system may fail if it fails to mitigate problems caused by longer droughts (e.g. by adequate storage facilities) or flash floods (e.g. by inundation areas).[29] In consequence, due to the lack of a common climatic character of most Mediterranean regions, averaged data must be verified for each individual case.

### 3.1.3 Surface runoff

Surface runoff can be generated either directly by rainfall or delayed in time by snow or ice melt. Typically, the latter is a seasonal phenomenon which is very important for mountainous river catchments and their subsequent discharge. Two major types of surface runoff can occur, depending on the precipitation rate and duration and the prevailing soil properties. One is excess overland flow, or Hortonian overland flow, which occurs when the rainfall rate is greater than the infiltration rate. This surface runoff type is typical for arid or semi-arid landscapes. The other surface runoff type is the saturation excess overland flow which occurs when rainfall continues after the soil pores are filled and saturated with water.[30]

The generation of surface runoff is tied to the drainage boundaries that define a watershed. Surface runoff can be classified according to its hydrological flow regime as perennial or temporal. Temporal streams, which do not flow throughout the year, may be of ephemeral, periodical or intermittent character.[31] Beside the temporal character of a flow regime, the water quantities (i.e. volume/time) are of interest. Of concern are large floods, in which the risk of disastrous impacts or irreversible shifts of river courses are inherent.

### 3.1.4 Groundwater

All water that infiltrates and fills the pores and spaces in the soil and rock basement become either interflow (in the unsaturated, or vadose, zone) or, if entering an aquifer, groundwater. Typically, groundwater is recharged by rainwater and flows following the hy-

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[26] Cf. García-Barrón, Aguilar, and Sousa 2011.

[27] Berking, Beckers, and Schütt 2010.

[28] Cf. Blumler 2005; Wagner 2001.

[29] Cf. Poesen and Hooke 1997.

[30] Quelle: Horton 1933; Berking, Beckers, and Schütt 2010.

[31] Elliot and Martin 2011.

draulic gradient until it reaches the surface and forms springs, oasis or wetlands. Groundwater that is not recharged is called fossil water.

With respect to surface runoff, the durability (perennial or temporal) of groundwater sources is of major significance for their exploitation. The type and material of the aquifer and its hydraulic conductivity (ease of throughflow), which determines the yield, are major influences on the durability. Groundwater bodies may undergo radical change due to tectonics. In the Mediterranean, the bedrock is often composed of limestone that eventually forms karstic aquifers.

It should be emphasized that the hydrological regimes of karstic regions are often more complicated than others because they often constitute underground drainage systems with sinkholes, dolines or caves. Due to the high permeability and instability of the formations, water can percolate quickly and thus be less purified to a lesser degree or more easily polluted than water in other regimes.

In summary: the topographic, geologic and climatic settings are of major importance for water availability. Especially in the Mediterranean area, the effect of the topographic setting and the underlying bedrock causes high variances of water availability over short distances. These variances lead to diverse physical processes in soil formation and erosion vulnerability, but also to different human settling and cultivation strategies. The resulting microregions and ecological mosaics are typical for the Mediterranean.[32]

## 3.2 Water technology

### 3.2.1 Transportation

The transportation of water is either natural (i.e. mostly gravitational) or facilitated by a construction designed to connect a target area with its water source(s). One could distinguish between surface and subsurface transportation and water allocation from within the catchment (water basin) or allocation from a distant watershed. Transboundary allocations of water in drainage basins, which go across administrative or national borders, have a special character, as they require special governance strategies.[33]

### 3.2.2 Target area

An area where water is used, applied or consumed can be described as the target (area) (Fig. 5).

### 3.2.3 Categories of water technology

Water technology can be divided into five major categories:[34]

- wells (springs),
- canals (open and closed),
- reservoirs (open and closed),
- dams (subsurface and surface),
- water-lifting devices.

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[32] Cf. Horden and Purcell 2000.

[33] Kucukmehmetoglu 2009.

[34] Cf. Garbrecht 1991.

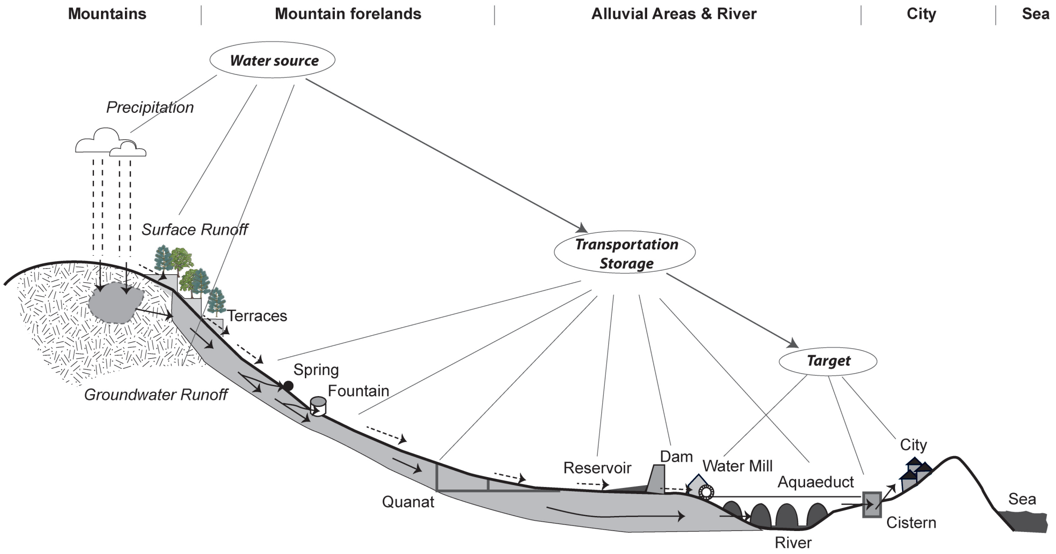

Fig. 5 | Sketch showing the arrangement of typical water sources, their means of transportation and storage as well as possible target areas in a landscape.

| | **Wells** | **Canals** | **Reservoirs** | **Dams** | **Water lifting devices** |
|---|---|---|---|---|---|
| *further categories* | springs | open or closed conduits | open or closed storage facilities | hydraulic design; rigid non rigid; structure; size; purpose | mechanical; automatically |
| *Major applications* | groundwater extraction | transportation, extraction, diversion, navigation | storage, improvement of water quality | temporal or permanent storage, sedimentation, flood control, energy, fishery, protection, recreation | fresh water, irrigation |
| *technical development* | from shallow earth holes to deep pumping wells | from earthen ditches to complex water conduits | from earthen ponds to complex storage facilities | from earthen embankments to complex river dams | from human powered to automated |
| *examples* | (artesian) springs | aqueducts, qanats, pipes | tanks, ponds, cisterns | terraces, gravity dams, arch (buttress) dams | Archimedean screw, pumps, water wheels |

Tab. 1 | The five categories of water technology with their major characteristics.

### 3.2.4 Aspects of the historical evolution and applications of water technologies

Those investigating the history of water technology face two major problems: (i) techniques are often difficult to date and published ages are often imprecise and (ii) artifacts or specific sites are not depicted in their entirety in the archaeological record (they are either buried or reshaped). The chronology of the presented examples must, therefore, be treated with caution – which is why we have indicated age and location only on a broad scale, i.e. on the regional and millennial scale. It is not within the scope of this paper to give a comprehensive or complete list of the history of water technology, though it does attempt to provide a structure and extract some major trends.[35]

The first or basic technique was most probably the direct extraction (tapping or withdrawal) of service- or drinking-water from lakes, rivers or water holes and the subsequent storage of this water for shorter time spans.[36] Of these, only the hand-dug water holes, probably the precursors of the first wells, should be treated as water technology. The oldest reported (preserved) wells are from the Clovis culture in North America and date back to the 12th millennium BCE;[37] the origins of the oldest wells known from the Mediterranean regions go back at least as far as the 9th millennium BCE, and they were found on Cyprus.[38]

A major transformation of water management probably came about with the establishment of irrigation measures in early agricultural societies.[39] However, these irrigation measures are typically suspected to represent forms of traditional water harvesting such as small irrigation channels or field terracing and as such are not long-lasting, dateable constructions. Indirect evidence indicates the existence of such measures in the Levante (Syria) for the 8th millennium BCE[40] and starting in the 7th millennium in the Kopet Dag Mountains (Iran and Turkmenistan[41]). In Egypt, flood water management is assumed to have started in the 5th millennium BCE,[42] and the first expanded irrigation and ample canal works are reported from Mesopotamia starting at least as early as the 4th millennium BCE.[43] The 3rd millennium probably marks the rise of 'high-energy' river engineering,[44] with the construction of the Sadd-el-Kafara Dam in Egypt,[45] the Marduk Dam in Mesopotamia and the Gabarbands in Balochistan, Pakistan.[46] In the 2nd millennium BCE, Hittite dams like the Karakuyu were built, and, in the 1st millennium BCE, the Ma'rib Dam in Yemen was built.[47] Early integrated and complex water management structures are known for the Harappa culture of the 3rd millennium BCE, which introduced a water management system including dams, canals, urban water supply systems, watered toilets and waste water outlets.[48] In the 2nd millennium BCE, a comparable system was

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[35] For comprehensive overviews see: Hassan 2011, Mays 2010, Ortloff 2009, Viollet 2007 or Garbrecht 1991.

[36] E. g. Baales 2012.

[37] Haynes et al. 1999.

[38] Tatton-Brown 1991; cf. Nir 1997.

[39] Sherratt 1980.

[40] E. g. Geyer and Besançon 1996 cited by Viollet 2007.

[41] Harris 2010; Wilkinson, Boucharlat, et al. 2012.

[42] Hassan 2011.

[43] Jacobsen and Adams 1958.

[44] Older dams were most probably not meant to be river dams, but only smaller earth dams for water retention, e.g. the earth dam at Jawa from the 4th millennium, Syria (Helms 1981).

[45] Garbrecht 1991.

[46] Brunner 2000.

[47] For more examples see also Garbrecht 1987.

[48] Cf. Kenoyer 2005.

introduced in Crete[49] and to some extents in the Moche valley in Peru.[50] At least as early as the 1st millennium BCE, a major transition took place with the tapping of groundwater and the introduction of the use of closed conduits (pressure water pipes) for long-distance transports. Such closed conduits diminish pollution, inhibit evaporation and hamper (illegal) water withdrawal. Examples for some early measures to harvest groundwater are the terracotta (clay) pipes at Pergamon, Turkey (see chapter 4.2.1 and e.g. Mays[51]). At the same time, the first groundwater canals (Qanats), too, occur in Mesopotamia (probably Urartu, though there is some discussion[52]). From the 1st millennium BCE onwards, the Hellenistic world in particular is cluttered with examples of water management techniques and an increase in knowledge about hydromechanics. The water pumps, water wheels, the Archimedes' screw and water mills are all innovations of this time, to name but a few. This marked change in our knowledge, too, of Hellenistic centered water works stems from the written sources and the long persistence of these techniques and achievements like the sophisticated management and regulation methods in the Roman Empire.[53] Indeed, Roman water management should be called the first integrated approach.[54]

It seems that, after the heydays of the Roman Empire and the preceding ancient cultures, no fundamental changes in water technologies took place for a long time. In fact, for nearly 2000 years, the applied technologies either remained the same or even declined,[55] until the onset of the Industrial Revolution, when the need for water for engine cooling opened up a new field of water usage. It took until the 20th century for multi-purpose storage (such as river dams for drinking water and electrical power) and, later, unified river programs to come into focus. It is not clear when the hydrological cycle and subsequently the internalization of a watershed-wide application of water management was first clearly understood. However, carrying out a full environmental and scientific assessment, including the protection of the resource water, is still a very young practice. It has only been within the last decades of the technological revolution that monitoring, decision support systems and communication plans are intended to cover and address all aspects of the means of an integrated water management.[56] Even today, an integrated and sustainable water management is more of an intended paradigm than a practical fact.[57]

## 3.3 Social organization

Water management is always performed to meet a certain *need* or, more specifically, to fulfill a *function* or *purpose* which necessitates any application. In consequence, water management cannot be reduced to the redirection of water from a source to a target area (Table 2). However, especially with respect to the archaeological record, in our case mostly artifacts of water technology, the intended functions of the observed techniques and measures are not always known. Moreover, several techniques may have served multiple functions at the same time. For example, an ancient canal (besides the notorious difficulty to date such artifacts) could have served multiple, very different purposes like *fresh water* or *irrigation*

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[49] Angelakis and Spyridakis 2013.
[50] Ortloff 2009.
[51] Mays 2010.
[52] Wilkinson, Boucharlat, et al. 2012.
[53] E. g. Bruun 2001 or Oleson 1984.
[54] Burian and Edwards 2002.
[55] Cf. Garbrecht 1991; Gleick 2002.
[56] Wescoat and White 2003.
[57] Biswas 2008.

*water transportation*, *navigation* or as part of *a protection measure* – or *a combination of these functions.*[58]

Other problems concerning the analyses of water management systems are the two dimensions of *time* and *scale*. As we have seen above, the categorization of an ancient canal with respect to function is already problematic; however, the difficulty becomes even greater when we assume that the system's function(s) may change over time. Natural processes, like siltation, flooding or decay of a canal, also occur as time passes. These processes are important categories of the analysis and introduce several problems that have hardly been studied in the context of water management systems at all, like *resilience*, *reliability* or *the maintenance expense.*[59]

Without a critical incorporation of various aspects and scales, the risk of being incomplete or deterministic seems evident. A famous example for an incomplete or deterministic analysis of this kind is the example of large-scale *irrigation*. Irrigation has long been believed to be a development with both cultural and social dimensions and to be responsible for the transition from hunter-gatherer societies to state-urban cultures and perhaps also to be responsible for the establishment of social stratifications.[60] Wittfogel states that for some ancient Asian societies the construction of large-scale irrigation works could only be explained by assuming a well-organized hierarchical state (bureaucracy) which availed itself of forced labor and engaged in organization.[61] Most scholars, however, disagree with the simplified and straightforward approach of the Wittfogel theory. The literature that rejects the hypothesis has already pointed out the problems inherent in such a general or deterministic way of viewing a complex system.[62]

| Function (equivalent or related terms) |
|---|
| Fresh water (domestic, drinking, tap, portable water) |
| Food production (irrigation, husbandry water) |
| Fishery |
| Navigation (transport) |
| Cult |
| Energy (hydropower) |
| Status (political power) |
| Hygiene |
| Entertainment |
| Protection |
| Cooling |
| Recreation |

Tab. 2 | Water functions.

In order to study water management, one must always include the people who use the water, those who build water harvesting and storage facilities and those who maintain these facilities. Socio-hydrological components and human decision-making processes are therefore of obvious relevance for the realization, functioning and maintenance. Who implements a component with which aim, based on what kind of knowledge and in what kind of environment are questions of major importance. Whether the water management

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[58] Cf. Stride, Rondelli, and Mantellini 2009.

[59] Cf. Lansing and Kremer 1993.

[60] Hunt et al. 1976; Wittfogel 1976.

[61] Wittfogel 1957.

[62] Ertsen 2010; Butzer 1996; Wilkinson and Rayne 2010.

system is established to serve the basic needs of drinking and agriculture or whether it is an expression of *governmental hubris* or *power* or of *cult* or *religious purposes* makes a huge difference.[63]

Especially for archaeological remains, scholars rarely have access to information on past human decision-making processes or knowledge about organization and coordination between different actors. Their analyses are generally based on artifacts, which they classified in order to analyze or evaluate them. This enables the comparison of systems like:

1. Ample irrigation canal networks are characteristic for many ancient urban kingdoms that evolved along great rivers like the Euphrates and Tigris, the Nile or the Indus River.[64]
2. Agricultural terraces, which are traditionally used to enhance crop yield by temporally storing water in the soil and sediment pores and, at the same time, to reduce soil erosion, occur globally independent of the climate regime and the crops cultivated.[65]
3. River engineering, e.g. the construction of dams, has been undertaken by nearly all societies in all fluvial systems for highly diverse purposes that can no longer always be distinguished, including navigation, power generation mining, recreation, storage of irrigation or drinking water; as above, functions might have changed over time.

These three examples document that *contingent*, *equifinal* or *emergent* features or processes frequently inhere in such comparisons. They correspond to complex, human-induced systems, so a description of the (inter-)actions by a purely physical approach is limited. Consequently, an adequate approach to study human-nature interactions is essential.

# 4 Case studies of the different approaches

## 4.1 The ‘hydro approach’

### 4.1.1 Naga

The city of Naga belonged to the so-called kingdom of Meroe and existed between the 4th century BCE and the 4th century CE in today’s northern Sudan. The prevailing arid climate with annual precipitation around 100 mm and high temperatures throughout the year indicate the dependency of the settlers on a well-organized water management strategy to cope with the overall arid conditions. In addition to the high temperatures, high evaporation rates and small amounts of rainfall, one should bear in mind that the next perennial river, the Nile, is 40 km away from the settlement, and that groundwater there lies at a depth of more than 70 m.[66] In consequence, Naga probably had to rely to a great extent upon the temporal storage of water in sufficient quantities and degrees of quality for its the water supply. Despite the small amount of annual rainfall, surface runoff, the result of the seasonal occurrence of the rainfall concentrated in only a few erratic events during the summer, was probably the main source of accessible water. The runoff was collected and mainly stored in an open, hand-dug reservoir, known as the Great Hafir of Naga.

[63] Ertsen 2010.

[64] Scarborough 1991.

[65] Krahtopoulou and Frederick 2008.

[66] Berking, Beckers, and Schütt 2010.

This approach, the storage surface of runoff in open water reservoirs, is a globally applied low-level technique or strategy with a long history, and is therefore often called "traditional"[67]. Such methods of water augmentation or storage are also called water harvesting methods. The example of Naga documents a good practical example of a self-sufficient and easily maintainable water management approach.[68] Above all, Naga is a nice example of the renaissance and persistence of traditional water management approaches. Recent development strategies for securing a water supply especially in remote regions and for irrigation purposes in Sudan list over 809 existing Hafirs and plans for construction of another 200 in 1982 (Fig. 6).[69]

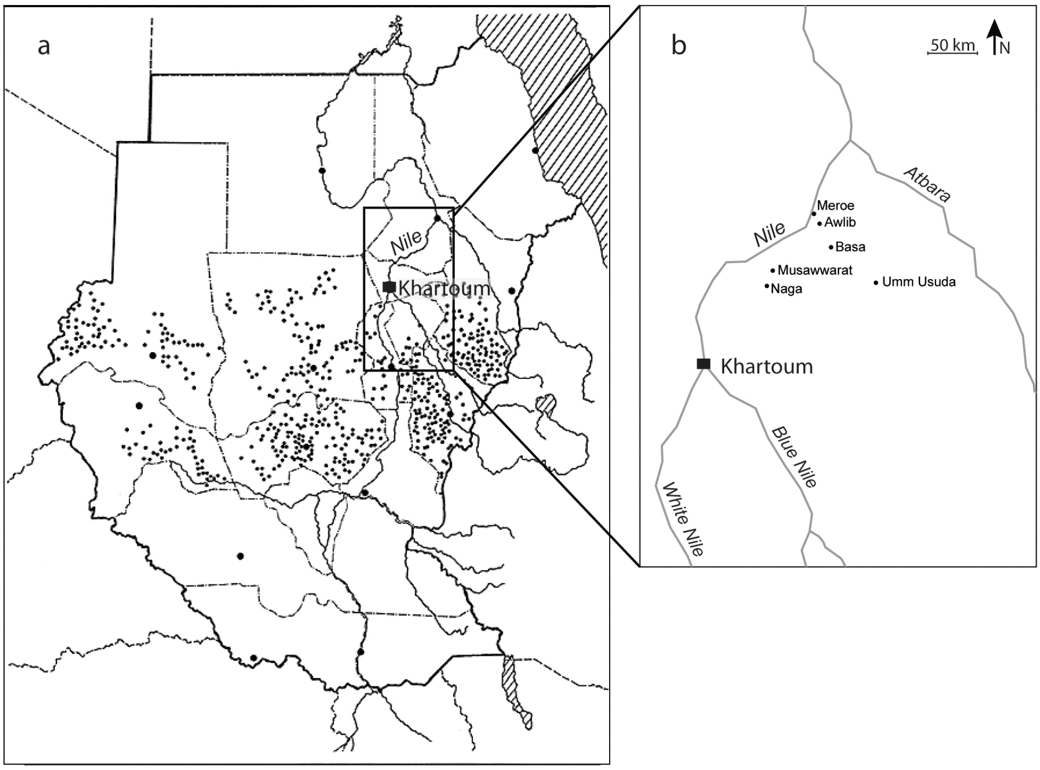

Fig. 6 | a) Distribution of modern Hafirs in the Sudan (North and South); b) distribution of ancient Hafirs.

## 4.1.2 Resafa

The Roman/early Islamic city of Resafa (Rusafa, Ar-Rasafeh) was founded as a fortified post in the northern steppe of Syria, 25 km south of the Euphrates, around 75 CE. Later, it became a pilgrimage site and was then sometimes called Sergiopolis. Especially during this later phase, it was a prosperous city with facilities such as a great city wall, a church and several cisterns. The climate is characterized by a dry steppe climate (summer-dry and winter-wet) with annual precipitation averages of 136 mm.[70] Like in the example of Naga, the high costs of transporting water from the next perennial river, the Euphrates,

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[67] Beckers, Berking, and Schütt 2013.

[68] Beckers, Berking, and Schütt 2013.

[69] Salih and Khadam 1982.

[70] Berking, Kaufmann, et al. 2011.

and the available brackish groundwater[71] both necessitate a self-sufficient or local water management strategy.[72]

An important part of this local water management strategy was the supply of drinking water via rooftop water harvesting and subsequent storage in bottle-shaped cisterns.[73] Brinker argues that the amount of water that could be stored in these cisterns was not sufficient to supply the city after the beginning of the 6th century,[74] and that therefore a much more efficient water source had to be harnessed. Archaeological findings document that these larger quantities of water were collected via a sophisticated floodwater harvesting system, including several technical structures such as a dam, spillways, settling and overflow tanks, and a central water harvesting facility, a big subsurface cistern. How many residents and visitors could be supplied from the subsurface cisterns is not known, and no reliable estimate exists. Given the dimensions of the cisterns, however, the number of residents and visitors in Resafa may frequently have been in the thousands, at least after the 7th century.[75]

From a general point of view, Resafa is, again, a good example illustrating the fact that the adaptation to and utilization of local rainfall and subsequent runoff lead to the most convincing results in the absence of potable perennial water resources in the direct vicinity of the settlement ,. The central facilities of Resafa were, in contrast to Naga, not open, but closed water reservoirs, i.e. cisterns. Cisterns of various designs and construction have been an essential part of water supply technology throughout history.[76]

## 4.2 The 'techno approach'

### 4.2.1 Pergamon

Pergamon, modern Bergama, was a city in western Anatolia located on the Barkircay River, the ancient Kaikos valley. The city itself was built on a mountain at 340 meter a.s.l. and 26 km east of the Mediterranean Sea. Pergamon gained its importance in Hellenistic times in the 3rd century BCE and later became independent and founded a dynasty. During Roman times, it also remained an important place and rose to a large city of up to 160 000 inhabitants. The water supply of the city was initially based on fountains and rock cisterns at the foot of the acropolis in which rainfall was stored.[77]

Probably in the second half of the 3rd century, a first long-distance water pipeline of about 15 km length was constructed, the so-called Attalos Aquaeduct that carried waters from the northern slopes to the city. This aquaeduct already shares the special features that were applied to facilitate the building of cisterns and wells (or fountains) on the city mountain: a pressure pipeline constructed of fired clay and an inverted syphon, realized through the application of communicating vessels.[78] Probably in the 2nd century BCE, the even more complex Madradag Aquaeduct, a triple pipeline of more than 50 km of length was constructed, one that, included a vaulted tunnel of 180 m of length and several settling basins that led freshwater directly onto the acropolis. The special features of this aquaeduct system were not only its sheer length, but also the construction material, which was most

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[71] Due to the parent gypsum basement.

[72] Beckers, Berking, and Schütt 2012.

[73] At least during its time as a small Roman military fort (until about the beginning of the 6th century) (Brinker 1991).

[74] Brinker 1991.

[75] Beckers, Berking, and Schütt 2012.

[76] Mays, Antoniou, and Angelakis 2013.

[77] Garbrecht 1991.

[78] Later on, the so-called Demophon Aquaeduct was built in the same manner.

probably lead, and its maximum pressure height of 190 m that had to be withstood.[79] It has been calculated that, at the end the 2nd century CE, the amount of fresh water available in Pergamon was as high as 26 000 $m^3$ per day, equal to an average of 160 l per day and person (with 160 000 inhabitants), which would be higher than, for example, the average present-day German consumption of about 121 l per day.[80]

The example of Pergamon shows that with the means of economic and engineering power, even quite unfavorable locations could be supplied with water. Such long-distance transportation of water to poorly supplied localities has been a common phenomenon ever since.

### 4.2.2 Merida

The city of Merida is located in southwestern Spain on the banks of the Guadiana River. It was founded as a colony for Roman veterans in 25 BCE by the emperor Augustus, and therefore was called Emerida Augusta. The city comprised a wide range of representative buildings such as a theater, an amphitheater, a circus, temples, bridges and aquaeducts, indicating the wealth and richness of this cultural and economic center.[81]

The prosperity of Emerida Augusta stemmed from two important facts: it was an assemblage of Roman elite veterans who had come to rest and spend the rest of their lives and money at this place and it also had an abundance of fresh water.

It seems clear that the Romans did not consider the waters of the river itself nor the probably easily reachable groundwater as sufficient water sources. Instead, they built a large hydraulic system with two capacious reservoirs as well as several aquaeducts to convey spring waters to the city.[82] The two main reservoirs from Roman times, the Cornalvo and the Prosperina Dams, are located 5 to 15 km north of the city, damming small tributaries of the Guadiana River (Fig. 7).

Both dams were built in the 2nd century CE as gravity dams. The Cornalvo Dam, which is probably the elder, of the two, had a wall length of 220 m and a reservoir volume of ~$8.5 \times 10^6$ $m^3$, whereas the Proserpina dam had a wall length of 427 m and a reservoir volume of ~$3.5 \times 10^6$ $m^3$ (Table 2).[83] It seems remarkable that both dams are still in good condition and have been working now for over 1800 years, although they have undergone several renovations since their construction. They are two among several Roman hydraulic structures that share such endurance.

| Name | Object Type | Length (m) | Width (m) | Height or Depth (m) | Volume ($m^3$) | Water Usage | Elevation (m a.s.l.) |
|---|---|---|---|---|---|---|---|
| Cornalvo dam | earthen dam | 220 | 7 | 20,8 | 8.500.000 | drinking water | 304 |
| Proserpina Dam | earthen dam | 427 | 3,8 | 18 | 3.500.000 | drinking water | 240 |

Tab. 3 | Comparison of the two dams.

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[79] Fahlbusch 2000.
[80] Cf. Fahlbusch 2000; Wilke 2013.
[81] McKenzie 2009.
[82] McKenzie 2009.
[83] Pinilla and Hernandez 1991.

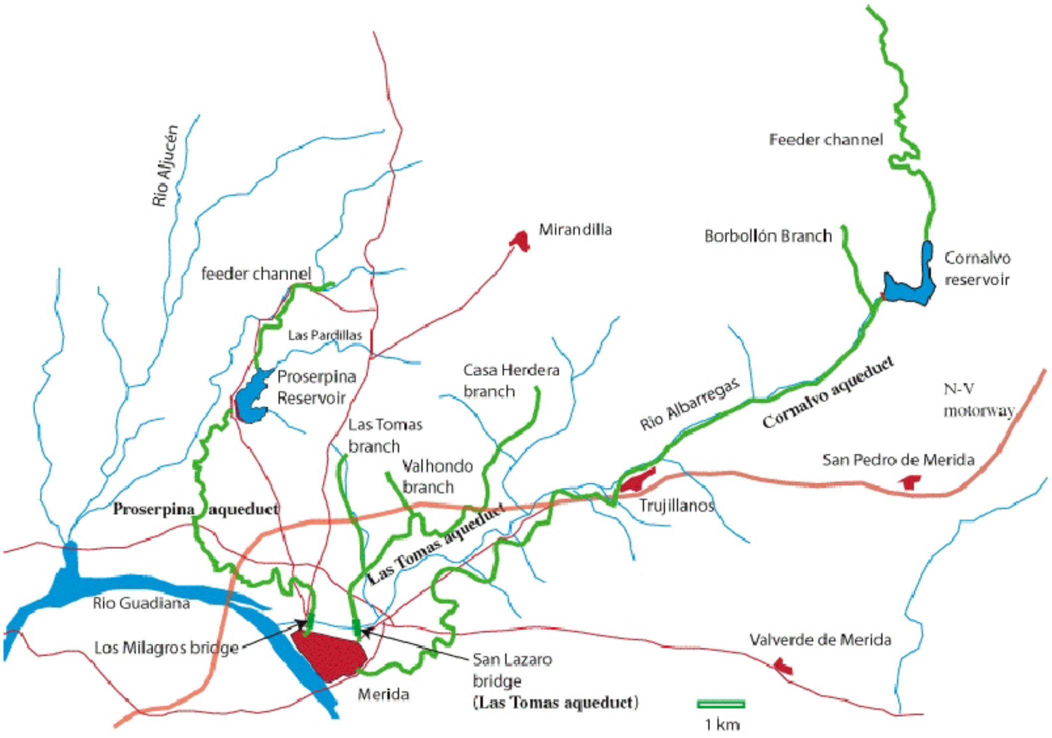

Fig. 7 | The water supply system of Merida.

## 4.3 The social approach

As Horden and Prucell[84] put it, water management "provides an excellent […] test case of the social impact of technological innovation". One reason for this appraisal is the character of the resource water: it has a high spatial and temporal variability; it has significance for the productivity of the primary and secondary economic sectors, and local usage of water can have a regional impact, i.e. upstream usage has a downstream impact. In consequence, the nature of water has held the potential for crisis and conflict, but also for cooperation throughout history. Therefore, the water management of social groups recorded in oral and written records and water works provide scholars from different fields, like history, law, anthropology and others, with material for studies on social and economic organization and conflict management.[85] Among the more prominent of these is the work of Thomas F. Glick.[86] Glick conducted a comprehensive study on the societal principals underlying the water distribution system in the Huerta of Valencia, a vast centuries-old irrigated area on the eastern coast of Spain. Here, water was mostly viewed as a common or public resource, and disputes over water distribution were often subject-matter in legal codes and were dealt with in what we know as water courts or tribunals. What the multiple studies on this issue show is that neither the environmental conditions nor the scale of the water management system nor the implemented technology solely determine the type of organization of societies or its vulnerability to crises.[87]

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[84] Horden and Purcell 2000, 238.

[85] Examples for this are the studies of Brunhes 1902; Wittfogel 1957; Glick 1970; Maass and Anderson 1978; Worster 1992; Boelens and Post Uiterweer 2013.

[86] Glick 1979.

[87] Glick 1970, 5.

# 5 Synthesis

Water management concerns can be analyzed in different ways: it is most common to focus the research on specific problems, applying established methods. We have called this kind of practices the 'hydro', 'techno' and 'social' approach respectively. For studies dealing with water management as a comprehensive issue, more holistic approaches are necessary, integrating in an ideal case all three aspects.

To integrate the analysis of water technology, water availability and social organization, we draft a first version of a human-landscape interaction concept that allows to compare otherwise rather incompatible studies. This becomes obvious when comparing the case studies of Naga (chapter 4.1.1) and Resafa (chapter 4.1.2). Here, specific societal conditions led to the foundation and continuation of these settlements in areas where the metabolism between human and nature relied on a considerable amount of societal labor. The two highlighted storage facilities for the water management of these settlements are illustrative artifacts for the societal organization at both sites. In view of their natural and economic settings, we expect that the costs and labor efforts to build them were high. The annual maintenance expenses to clear the storage facilities were probably also high. We do not know on what knowledge the technologies used to supply the settlements Naga and Resafa with water were based on, but it is clear that they changed the metabolism (e.g. the fresh water availability) for the two towns and their environments (e.g. agriculture) during their existence.

Interestingly, these methods of surface water augmentation have been applied successfully in numerous other dryland areas until today. Though the techniques might be classified as sustainable or at least long-lasting. It is, therefore, society that creates the frame: when the metabolic costs cannot be afforded anymore, a system collapses, independent of its sustainability in ecological terms. This is a very important point, especially with respect to modern discourse, in which traditional water management methods are drawing increasing interest from researchers. Finally, we wish to point out that the evaluation of water management issues is of great interest in modern times, but is only possible when those issues are (rendered) comparable.

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FIGURES: 1 Jonas Berking. 2 Jonas Berking. 3 Jonas Berking. Modified after: Fischer-Kowalski, Mayer, and Schaffartzik 2011. 4 Jonas Berking. 5 Jonas Berking. 6 a: © FAO 1990. *Source Book for the Inland Fishery Resources of Africa*, fig. 3. http://www.fao.org/docrep/005/t0361e/t0361e07.htm (visited on 04/04/2016). 6 b: after Kleinschroth 1987. 7 © 2004–2016 Cees Passchier, with kind permission. http://www.romanaqueducts.info/aquasite/merida/foto1.html (visited on 04/04/2016). TABLES: 1 Jonas Berking. 2 Jonas Berking. 3 Extract from the Topoi water-database, data provided by Pinilla and Hernandez 1991.

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