Comparative case study analysis of adaptive groundwater governance and management regimes:
Exploring ecosystem services in South Africa, Spain and Germany

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THESIS

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Summary

Our daily lives depend on the provision of services by different ecosystems. Ecosystem services refer to those ecosystem functions and processes that are actively used, enjoyed or consumed by humans (Gómez-Baggethun and de Groot 2010). Daily (1997, p 3) defined ecosystem services as, “the conditions and processes through which natural ecosystems and the species that make them up, sustain and fulfill human life.” Ecosystem services have become a key concept in sustainability research and are beginning to find their way into policy-making through international projects such as the Millennium Ecosystem Assessment (MA).

Groundwater resources and the services they provide make an important contribution to human well-being. In many countries groundwater is the main source of freshwater and is, therefore, particularly important to society’s ability to meet basic human needs (e.g., water for cooking and drinking, sanitation and health) as well as socio-economic development and growth (Burke and Moench 2000, Mukherji and Shah 2005). Furthermore, groundwater plays a crucial role in maintaining the environment and water-related ecosystems such as rivers, wetlands, swamps and marsh land (Danielopol et al. 2003, Steube et al. 2006).

The traditional hierarchical and technocratic focus of groundwater management has led to major shifts in the landscape water systems of many regions of the world and the consequent degradation of ecological flows. Guaranteeing sustainable resource management is, therefore, one of the central tasks of the 21st century (UNEP 2007, Bates et al. 2008).

The overuse of aquifers has resulted in the modification of groundwater resources, diverse trade-offs and the complete loss of ecosystem services. For a long period of time, theories and approaches to natural resource management largely focused on single and fragmented system elements (e.g., technological development) and were based on a steady-state view. However, interpreting change in complex social-ecological systems (SESs) as gradual, incremental, while ignoring interactions across space and time, does not facilitate sustainable management (Folke et al. 2005). Such approaches are of limited use in analyzing and understanding the complexity of governance regimes, ecosystem services and the human dimension.

The degradation of groundwater ecosystem services (GESs) has many complex causes, and management often fails to account for linkages between different services. Many of these problems in water management are associated with the failure of governance regimes[1] (Bakker et al. 2008,

[1] A regime is understood here as, “the whole complex of technologies, institutions, environmental factors and paradigms that are highly connected and […] form the base for the functioning of the management system targeted to fulfill a societal function” (Pahl-Wostl 2009, pp. 354–365).

Rogers and Hall 2003). In addition, aquifer systems are complex, difficult to understand, and the consequences of human interventions are difficult to predict (Seward et al. 2006). It is suggested that the way forward is to accept the complex and uncertain characteristics of groundwater, and to develop management approaches around these characteristics, rather than to ignore them. Groundwater management, therefore, requires innovative approaches dealing with system complexity. One such approach can be found in adaptive management, which constitutes the only viable means to deal with the uncertainties in knowledge and the variability of societal attitudes towards groundwater resources (Maimone 2004, UNESCO 2006).

Therefore, the main objective behind this study was to analyze whether there is a relationship between adaptive groundwater governance and management regimes and the state of GESs.

As groundwater management falls under a range of different remits including economics, law, public policy, science and technology, an inherently inter-disciplinary research design was chosen for the study. The study draws on the conceptual foundations of adaptive management and governance, ecosystem services and the role of institutions in exploring a way towards the sustainable management of GESs. First, adaptive management and governance regimes consider uncertainties explicitly and require a basic rethinking of what management means in an uncertain and changing environment with various complex SESs (Pahl-Wostl et al. 2007). Second, the concept of ecosystem services is deemed to be an approach complementing adaptive management and was successfully introduced into the global policy arena by the Millennium Ecosystem Assessment (MA 2005). It has been welcomed by both conservationists and natural resource managers as a potential bridge between the biodiversity and sustainable development discourses (Tallis et al. 2008). In spite of the apparent success of this concept, progress in terms of practical application in resource planning remains slow (Naidoo et al. 2008, Daily et al. 2009). Environmental problems often arise from deficient, uncertain or confusing information about which ecosystem services are available, how they are important for humans, combined with incomplete, inconsistent or unenforceable rules, rights and responsibilities. Hence, a third approach used in this study is the responsiveness of institutions and their effectiveness in relation to SESs. Institutions describe the central behavioral tendencies of management and governance, and the social dynamics that result from different hydro-geological and environmental conditions. Furthermore, institutions may be used to mediate the link between ecosystem services and the constituents and determinants of human well-being (MA 2005, Gómez-Baggethun and Kelemen 2008).

Up to now, analytical frameworks to explore complex system linkages and feedbacks between governance regimes, GESs, human well-being, and the state of the overall ecosystem are rare. This thesis fills this gap. It builds upon the management and transition framework (MTF) developed by

Pahl-Wostl and colleagues (Pahl-Wostl 2009, Pahl-Wostl et al. 2010). To this end, a corresponding database approach was applied in order to analyze groundwater governance regimes and complex management processes. The MTF was applied as an analytical tool by using its modeling language to describe different case studies in order to compare them. Case studies can help focus on the significance of the idiosyncratic as well as in the identification of general patterns of adaptive governance regimes. The framework supports the analysis of groundwater systems, the ecosystem services they provide and governance and management regimes to improve the scientific understanding of system properties. The application of the framework ensures that all of the case studies are represented in a standardized and comparable way (Knieper et al. 2010). A novel aspect of this study was, therefore, first tailoring the MTF to the specific research needs and second applying the framework to empirical case studies.

The analytical research was based on the argument that the sustainable management of GESs requires adaptive governance and management regimes characterized by ecological understanding and learning environments that adjust their responses in order to deal with change and uncertainty (Berkes et al. 2003, Ostrom 2007). The analytical focus of this thesis was placed on the investigation of vertical (hierarchies) and horizontal (sectors) integration structures assumed to be crucial characteristics of an adaptive groundwater governance and management regime. The study built upon criteria and indicators to characterize vertical and horizontal integration (e.g., interaction and cooperation between different administrative levels and sectors, involvement of local stakeholders during planning and decision-making processes). Moreover, an emphasis was placed on the investigation of the institutional response, including different drivers of change. Both formal and informal institutions were investigated so as to identify integrative perspectives for the use and protection of GESs.

The overall goal of the study was to provide empirical evidence, largely lacking to date, derived from comparative analyses carried out over the course of field research made as part of three case studies: the Sandveld (South Africa), the Upper Guadiana Basin (Spain) and the Spree Basin (Germany). As the context and history of the case studies were deemed to be preconditions for understanding governance and management regimes, and for the transition towards more adaptive behavior, an analytical timeframe of more than twenty years was chosen. The process of data collection was based on intensive primary and secondary document research and a series of qualitative expert interviews. The interviewees reflected various types of expertise and knowledge: politics and administration, consultancy, water supply, forestry, research and nature conservation. Prior to data collection, general processes and actors in groundwater management were identified. For a more precise description of these processes, including system linkages and feedbacks, the interviewees were asked to outline a sequence of groundwater policy and management processes covering the past 20-25 years in order to identify a transformation towards more adaptive management. Once data collection was completed, all of the information was input into Microsoft Office Access databases and systematically analyzed. The analysis was conducted by means of a set of standardized protocols (=queries) to filter and sort the information required to answer the research questions concerning the groundwater governance regime and the linkages to GESs.

The results of the study indicated that the services provided by underground water resources, and the ecosystem services approach, are not widely acknowledged in the political and institutional arena of groundwater management. The linkages between the groundwater governance regime and GESs are very diverse, and processes towards sustainable and adaptive management vary in the three case studies. Overall the general awareness and significance of GESs supporting human well-being increased where vertical and horizontal integration structures are in place. However, the results also indicated that a higher degree of integration in management activities and the involvement of stakeholders (e.g., farmers, municipalities) does not necessarily lead to a direct improvement of GESs. Nevertheless, the evidence revealed that a higher degree of integration:
(i) opens up the political arena for environmental perspectives,
(ii) increases the quality of groundwater and conservation plans,
(iii) accelerates the implementation of measures,
(iv) mitigates conflicts between different groundwater users, and
(v) increases the awareness of different GESs.

Despite case study-specific variations, the findings revealed that institutional response evinces certain common trends whereby provisioning services are favored over regulating and cultural services. The evidence suggested that (a) institutional response is at an early stage in terms of incorporating integrative perspectives of GESs and (b) the presence of well-crafted institutions does not automatically indicate successful groundwater management in the sense of bringing about positive results for social, economic or ecological sustainability.

The study provides scientific foundations to support policy advice, including the role of adaptive governance, and the corresponding institutions governing ecosystem services, in the context of groundwater management. In general, the results of this study confirmed the statements of the MA (2005) proclaiming that ecosystem service trade-offs arise from management choices made by humans and that changing governance structures towards more adaptive and sustainable management is a challenging and long-term process requiring a break with traditional structures and an abandonment of long held habits, which will take decades rather than years. Therefore, new approaches and practices to steer current groundwater management towards an adaptive and sustainable form of management must incorporate an adaptive capacity accounting for GESs as a bridging part of SESs.

This piece of interdisciplinary work brought together research approaches from the natural and social sciences in an attempt to render governance and management, and their linkages to the natural resource base, more transparent.

The thesis provides different options for the investigation of further research questions: who determines which ecosystem services should be prioritized for protection, what components of these services should be valued, how do ecosystems and their services change over time, and what are the major consequences for human well-being? More empirical evidence from global and sub-global case studies from around the world is required in order to answer these questions and to contribute to the establishment of a scientific knowledge base for present state and future scenarios of ecosystem services and SESs.

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List of Abbreviations

AA	Action arena
AS	Action situation
DWA	Department of Water Affairs (of South Africa)
EU	European Union
FÖNAS	Förderverein für Naturschutz im Spreewald (Sponsor Association for Nature Conservation in the Spreewald*)*
GCBC	Greater Cederberg Biodiversity Corridor
GES	Groundwater ecosystem services
GRSP	Gewässerrandstreifenprojekt (Spreewald Riparian Land Projekt)
IWRM	Integrated water resources management
MA	Millennium Ecosystem Assessment
MTF	Management and transition framework
NGO	Non-governmental organization
PEP	Pflege- und Entwicklungsplan
RBA	River basin authority
SES	Social-ecological system
SPUGB	Special plan for the Upper Guadiana Basin
TSD	Total system database
UGB	Upper Guadiana Basin
WAP	Water abstraction plan
WFD	Water Framework Directive

1. Aim and scope of the study

The sustainable management of groundwater resources is becoming increasingly important and requires adaptive approaches and integrated institutional responses that take into account the huge variety of ecosystem services provided by groundwater and aquifer systems. A major issue with respect to sustainable groundwater management is the need to give consideration to groundwater ecosystem services (GESs) and their linkages and trade-offs, as these are important to different industrial sectors: agriculture, mining, forestry, fisheries, urban and rural water suplly, tourism, and conservation.

Understanding the complexity of governance and management regimes and recognizing human and biophysical characteristics as intertwined components of socio-ecological systems (SESs) is crucial. The term management refers to activities in the analyzing, monitoring, developing and implementing of measures to maintain natural resources in a state that is within desirable limits. The term governance on the other hand refers to the actors and networks that formulate and implement policy. Governance sets the overall rules under which management operates (Pahl-Wostl 2009). The term 'groundwater governance and management regime' is hereafter referred to solely as groundwater regime.

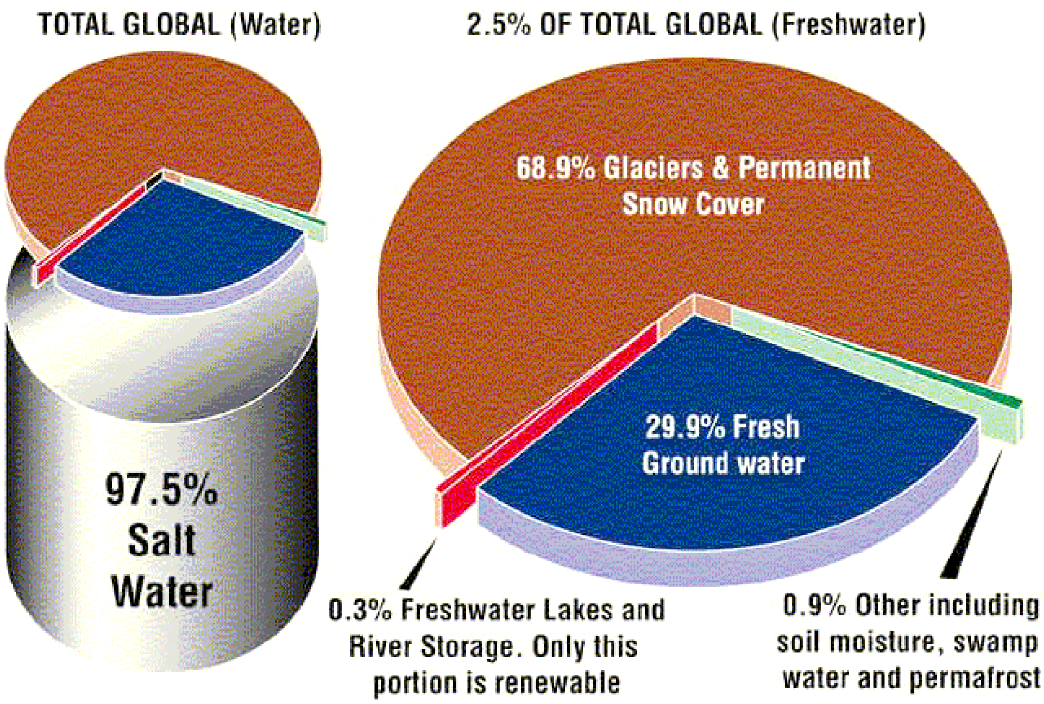
Approaches and analytical frameworks exploring the linkages and feedbacks between groundwater regimes, GESs and human well-being nested in complex SESs are rare. This thesis fills this gap. The overall assumption is that the sustainable management of GESs requires groundwater regimes characterized by ecological understanding and learning environments that adjust their response in order to deal with change and uncertainty (Berkes et al. 2003, Ostrom 2007).

Vertical (hierarchical) and horizontal (cross-sectoral) integration structures are crucial characteristics of an adaptive groundwater regime. Institutions are an important element of groundwater regimes governing GESs as they offer a major source of stability and strength in providing diverse ways of coping with change and uncertainty.

Presented in this thesis are the results of a comparative case study analysis, the aim of which was to investigate the groundwater regime nested in complex SESs, in order to achieve a deeper understanding of how GESs are structured and governed between natural and human water needs.

1.1 Outset and research motivation

Groundwater is the Earth's largest accessible freshwater store and constitutes about 94 % of all freshwater resources, excluding ice sheets and glaciers (**figure 1**) (Ward and Robinson 1990). On a global scale, one third of the human population depends on groundwater, in urban as well as in rural areas, and in low- as well as in high-income countries (Hetzel et al. 2008). Groundwater resources, and the ecosystem services they provide, are not merely important in providing benefits to humans (e.g., high quality of water for drinking, cooking, sanitation, agriculture and industrial use), they further regulate different ecological functions and processes (e.g., self-purification, base-flow to rivers, wetlands and springs, buffer during droughts) and provide a habitat for highly adapted micro-organisms and groundwater fauna (Bergkamp and Cross 2002, de Groot et al. 2002, Danielopol et al. 2003). The Millennium Ecosystem Assessment (MA) (2005) developed four broad categories to distinguish ecosystem services: provisioning (e.g., water supply), regulating (e.g., drought or flood attenuation), supporting (e.g., nutrient cycling) and cultural (e.g., recreation) services (**chapter 3.2**). This categorization serves as a functional abstraction from ecological resources to 'used services' that highlights the linkages and dependencies between these services and human well-being (Loring et al. 2008).



(source: http://scienceforums.com)

Figure 1 Distribution of global water resources

For a long time little was known about the institutional arena governing groundwater systems and ecological processes and functions (Mukherji and Shah 2005). Nowadays, hydro-geological tools and approaches to guide groundwater development and protection are manifold: field mapping and remote sensing, geophysical surveys and logging systems, water-well drilling, chemical and isotopic analysis, groundwater protection zoning, economic instruments such as taxes and tradable permits, to name but a few. Management has started to consider the environmental dimension of groundwater, and the dependent ecosystems, and sustainability has become an important principle in groundwater governance, including an integrative perspective of social, economic and ecological systems. Although institutions have started to consider groundwater not only as a resource but also as a living ecosystem (Steube et al. 2006), comprehensive institutional response to GESs, including the social and ecological dimension, as an integrated system remains relatively rare, and in some regions of the world is still completely absent. Institutions are the prescriptions that humans use to organize all forms of repetitive and structured interactions (Ostrom 2005). Institutions are made up of (i) formal, legally binding constructs (e.g., directives, laws, conventions) created through official channels of governmental bureaucracies and enforced by state agencies and (ii) informal, mostly unwritten and non-codified constructs (e.g., socially shared rules, self-imposed regulations) developed and enforced outside of legally sanctioned and public channels (North 1990, Pahl-Wostl 2009).

However, the assessment of the environmental impacts of intensive groundwater exploitation, water quantity and quality standards, and the protection of GESs is often not as straightforward as it is officially stated in many countries, and the degree of degradation remains high. Consequently, the equitable and sustainable provision of GESs remains an unfulfilled issue. One reason for this is that the common-property characteristic of groundwater and the invisible nature of aquifers, combined with the often intangible nature of the services they provide, creates challenges for the development of effective institutions (Burke and Moench 2000).

Water managers frequently overlook certain critical linkages that exist between groundwater resources and the ecosystem that provides services and which, in turn, support the resource base embedded in the overall management context. Furthermore, environmental problems often arise from deficient, uncertain or confusing information about the availability of GESs and their importance to humans and ecosystems, combined with incomplete or unenforceable rules, rights and responsibilities (Hanna et al. 1996). This disproportion often leads to trade-offs between GESs essential for life, which vary in time and space. Linear causal patterns of the linkages between ecosystems, ecosystem services, human well-being, human response and feedbacks to drivers of change are rarely observed (Carpenter et al. 2009). In general, the degradation of natural water resources has many complex causes, which are associated with failures of governance rather than with the actual resource base (Bakker et al. 2008, Rogers and Hall 2003). According to Turton et al. (2006), governance is “the process of informed decision-making that enables trade-offs between competing users of a natural resource so as to balance protection and use in such a way as to mitigate conflicts, enhance security, ensure sustainability and hold government officials accountable for their action.” Hence, governance needs to take into account the increasing importance of modes of governing, where non-state and private corporate actors participate in policy formulation and implementation, and develop instruments that co-exist alongside government policy processes. In relation to groundwater resources, the definition provided by Foster et al. (2009) appears apt. They stated that governance includes, “the fulfillment of appropriate authority and promotion of responsible collective action to ensure sustainable and efficient utilization of groundwater for the benefit of humans and dependent ecosystems.”

According to these rather normative descriptions of groundwater governance, it is vital to highlight the need for integrative and cooperative management at all levels – from local to international – as well as the active involvement of different stakeholders and sectors to ensure the sustainable utilization of groundwater resources. The definition provided by Foster et al. (2009) makes clear that governance must view human and bio-physical systems as intertwined components by taking into account both human benefits and the maintenance of GESs.

Given the concerns outlined above, the motivation for the research presented in this thesis was reinforced by the following facts:

- Lack of knowledge and exploration of GESs:
    - The intensive use of groundwater and the acknowledgement of GESs date back just half a century in many countries. Consequently, there is a lack of research experience regarding the impacts of management on resource. Interdisciplinary research on GESs and human well-being comprising both the social and the ecological dimension is especially rare.
- Lack of empirical evidence:
    - Empirical evidence derived from case study research exploring ecosystem services is rare, and almost non-existent in the case of GESs. Unfortunately, environmental problems often arise from deficient, uncertain or confusing information about what GESs are available and how they are important to humans, combined with incomplete, inconsistent or unenforceable rules, rights and responsibilities. To close this gap and to better understand the requirements of groundwater management, the case study research method was employed in this study. This made it possible to conduct a detailed and in-depth analysis of the groundwater regimes of different locations.

- Lack of analytical frameworks:
    - Approaches and analytical frameworks to analyze linkages between groundwater regimes and GESs are rare. Investigating the characteristics of groundwater regimes and processes of change towards more adaptive and sustainable resource management requires a framework of intermediate complexity (Pahl-Wostl 2009). Here the MTF was employed, and further built upon, in order to support context-sensitive analysis to provide insights into both the structural conditions of SESs and diverse performance measures of groundwater regimes.

1.2 Objectives and research questions

The study presented in this thesis investigated the complexity of groundwater regimes and reconstructed policy and management processes in individual, detailed case studies in order to reveal the relationships between groundwater regimes and GESs nested in complex SESs. Finding ways to govern these systems sustainably has become ever more difficult as they have become increasingly interlinked (Ostrom and Cox 2010). One of the central objectives of the study was to compare the performance of groundwater regimes impacting upon GESs. The case study method was especially appealing as a means to analyze complex system linkages and feedbacks, and to provide an adequate option for empirical field-based research where cross-case data where not available (Potetee et al. 2010).

To obtain workable and meaningful analytical results, regime characteristics that are significant for adaptive groundwater management were analyzed as part of the study: vertical and horizontal integration as well as the institutional response governing GESs. Comparing the case studies and meeting the research objectives required a framework that provided a certain degree of formalization and standardization in terms of data collection and analysis protocols. This was the reason for employing the MTF and a corresponding database approach to analyze the vertical and horizontal integration of the regime characteristics in order to render complex management processes more transparent.

In order to detect changes to and transformation processes affecting groundwater regimes, the analytical time horizon encompassed more than twenty years in each case study. The empirical research focused on groundwater management at sub-basin level, considering also the national and international context of each case study.

Table 1 contains three research topics and corresponding research questions addressed in the study.

Table 1 Research topics and questions addressed in the study

Research topic 1: Framework development	
1a)	What are the requirements of an analytical framework supporting the context-sensitive case study analysis of groundwater regimes governing GESs?
Research topic 2: Groundwater regime characteristics: vertical and horizontal integration	
2a)	How does vertical and horizontal integration evolve in each case study?
2b)	Does a higher degree of integration foster the sustainable management of GESs?
Research topic 3: Drivers of change and institutional response	
3a)	What are drivers of change and how do they impact upon institutional response in each case study?
3b)	Does the institutional response incorporate integrative perspectives on GESs towards effective groundwater ecosystem management?

Research topic 1 served as a conceptual and theoretical construction to accomplish the empirical case study research. It included the development of a framework relevant for the comparative case study analysis. **Question 1a** was deemed to be an essential starting point for the study. The framework builds upon the MTF and was further tailored to explore the relationships between groundwater regimes and GESs.
The conceptual development and requirements of the framework are outlined in paper 1. The explorative analysis of the Upper Guadiana Basin (UGB) in central Spain exemplifies the potential of the framework: examination of vertical integration during the process of formulating the Special plan for the Upper Guadiana Basin (SPUGB).

Research questions 2a and **2b** explored the vertical and horizontal integration of the groundwater regime characteristics. Criteria and indicators were developed to analyze integration structures across case studies. The focus of the comparative research was placed on the interplay between different hierarchal levels, networks of state and non-state actors and sectoral cooperation during groundwater ecosystem management.

Research topic 3 linked the role of institutions and ecosystem services to the overall context of groundwater management. Under **research question 3a** different drivers of change associated with economic or political shifts, ecological drivers and society-induced changes were identified. Under **research question 3b** the effectiveness of and integrative perspectives on GESs were explored.

The conceptual, methodological and analytical procedure underlying the study can be summarized in four broad steps. Firstly, theoretical and conceptual approaches suitable for the development of the framework were reviewed. In a second step, linkages between a groundwater regime and GESs were identified and data collected. Thirdly, data were systematically explored with the help of the framework. Finally, the empirical results were underpinned by literature reviews.

1.3 Structure of the thesis

The thesis has been written cumulatively and contains two papers published in peer-reviewed journals (attached to the thesis). Further a supplementary study is attached to the main body of the thesis. Parts of the research presented in the thesis were linked to the cooperation project 'Mainstreaming Climate Variability and Climate Change into Policy and Decision Processes for Adaptation in Water Resource Management' undertaken by the University of KwaZulu Natal (South Africa) and the University of Osnabrück (Germany) with the financial support of the German Federal Ministry of Education and Research (BMBF) and the South African National Research Foundation (NRF).

The complexity of the research was illustrated in the thesis summary, in which it was possible to consider in somewhat greater detail the characteristics of groundwater resources and the services they provide than was the case in the papers where space was limited. The summary further provided an opportunity to explain the background to the individual case studies chosen for the comparative analysis and to present the methods and the analytical framework more precisely.

Figure 2 provides a schematic overview of the relationship between the research topics, the research questions, the case studies and the papers. The thesis is structured as follows. Based on the results of a literature review, the research context and the challenges are outlined in **chapter 2**. First, GESs including hydro-geological characteristics, human well-being and trade-offs are introduced. Next, the challenges on the path towards adaptive groundwater management, the complexity of SESs and the challenges facing groundwater governance overall are highlighted. **Chapter 3** provides an overview of the underlying concepts of the thesis, which draw upon three complementary approaches: adaptive management and governance, the ecosystem services concept, and formal and informal institutions and their role in groundwater management.

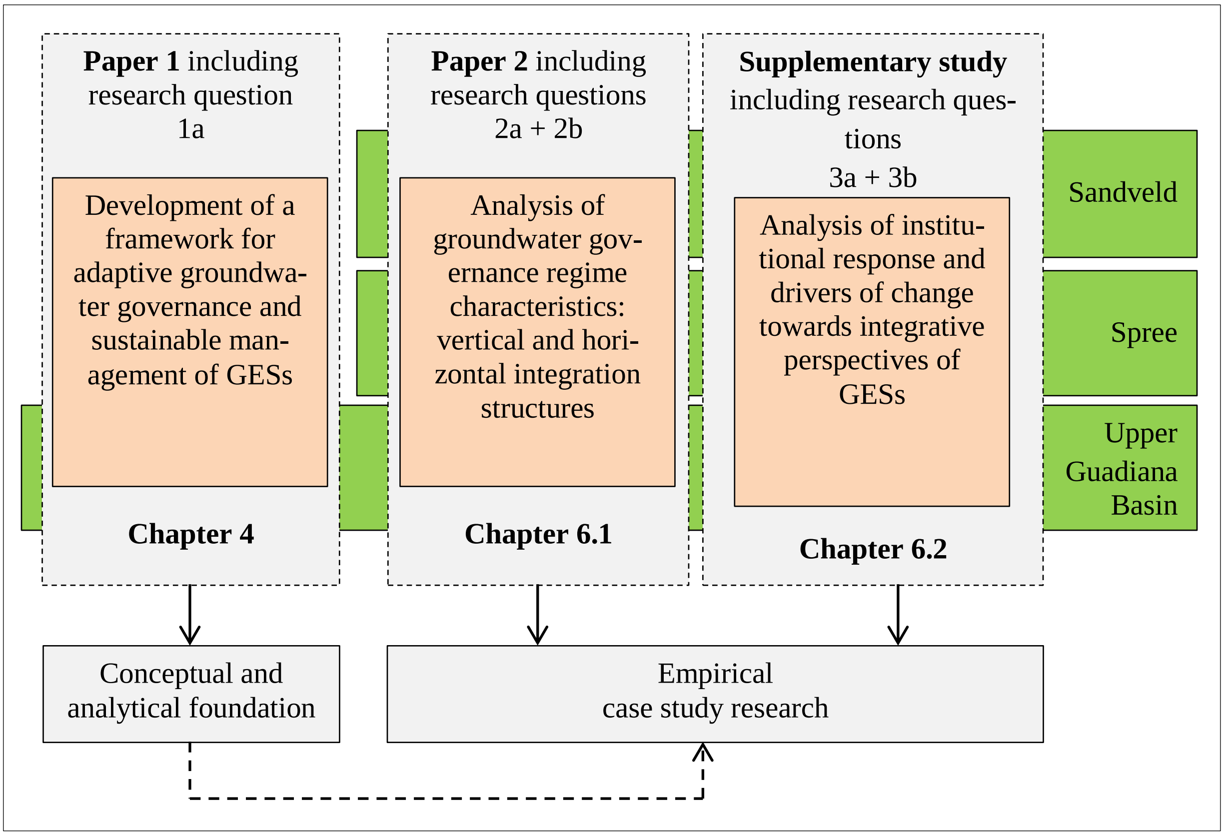


Figure 2 Schematic structure of the thesis

The methods and the development of the analytical framework used for the empirical research are explained in **chapter 4** (paper 1). After an introduction to the case study research method, a detailed explanation of the MTF and its elements is provided. **Chapter 5** introduces the three case studies including the corresponding challenges in relation to groundwater governance and management.

The central focus of the thesis is highlighted in **chapter 6**. The results and discussion of the empirical research are taken up and discussed with regard to the research questions outlined in **table 1**. The presentation of the key findings within the thesis follows the structure as represented by paper 2 and the supplementary studie.

Chapter 7 contains the conclusions drawn from the main findings and the overall contribution of the analytical framework to the comparative case study analysis. A critical reflection on the study is also provided, including an assessment of the research design and the analytical results. Finally, some perspectives on further research in the broader context of natural resource management are proffered.

The two papers and the supplementary studie are presented separately from the main body of the thesis:

In paper 1 the development of the novel framework built upon the MTF in order to analyze governance complexity, GES linkages and trade-offs, and transformation processes is presented. The UGB was chosen to analyze the degree of vertical integration during the development of the SPUGB so as to illustrate the benefits and potential of the framework.
In paper 2 the results of the comparative case study analysis of vertical and horizontal integration are illustrated, and the linkages between groundwater regimes and the state of GESs identified.
In the supplementary study the links between the role of institutions and ecosystem services in the overall context of groundwater ecosystem management are highlighted. The contents of the supplementary study derive from empirical evidence from the three case studies. In the supplementary study insights into the institutional response to different drivers of change and the effectiveness in relation to GESs are provided.

2. The research context and the challenge

2.1 The context: Groundwater from an ecosystem services perspective

Groundwater is, in most situations, characterized as being a common pool resource, with relatively little public awareness with regard to the resource behavior, the benefits it confers and the limits to its availability (Burke and Moench 2000). The common pool nature of groundwater contains the attributes subtractability and excludability, which makes the protection of GESs and the effectiveness of governance with respect to the day-to-day livelihoods of people even more difficult. Subtractability refers to the fact that GESs have a limited capacity, whereby the consumption of groundwater by one user subtracts from the flow of GESs available to others (Ostrom 2005). Excludability refers to the fact that it is difficult to prevent water users – especially landowners and farmers – from pumping water from aquifers.

Groundwater resources can be looked at from different angles (e.g., hydro-geological, chemical, biological or technical) and provide a wide field of research questions. Within the scope of this study, the ecosystem service perspective was chosen to look at groundwater resources as it bridges the ecological and the social dimensions. This perspective highlights the many different functions and processes of groundwater in supporting human well-being. Many ecosystem services have a direct link to groundwater storage, recharge and discharge, and also offer a wide variety of marketable goods and non-market services (Foster et al. 2003). Cork et al. (2001) referred to ecosystem services as "a transformation of natural assets into products that are important to humans." For example, discharge of groundwater into streams and rivers may provide essential nutrients to aquatic life and support downstream water users with respect to drinking and irrigation (NRC 1997). Apart from a wide range of production and consumption processes, GESs also provide a variety of other functions, such as purification processes, regulation of the water cycle, and the maintenance of biodiversity (Bergkamp and Cross 2002, de Groot et al. 2002).
Provided in **table 2** is an overview of GESs and the corresponding ecosystem services according to the MA categories, which are further explained in **chapter 3.2**.

Table 2 Overview of the groundwater ecosystem services analyzed in this thesis

GES	Ecosystem service type	Explanation
Irrigation	Provisioning	Groundwater is a store and retention basin for irrigation in agriculture. The scale and rate of groundwater use for irrigation has increased substantially due to the massive expansion in pumping capacity.
Domestic supply	Provisioning	Groundwater is used for drinking and cooking as well as for sanitation and washing requirements as a basic human need.
Power plants	Provisioning	Groundwater is used in lignite power plants, as a means of cooling components and industrial equipment (in the context of coal mining).
Purification/ waste treatment	Regulating	The biological component of the groundwater environment provides an important service in the form of water purification and waste treatment through the microbial degradation of organic compounds and potential human pathogens.
Drought buffer	Regulating	Groundwater acts as the primary buffer against the impact of climate variability and spatial variability in the event of drought. The buffering potential depends on the soil and rock types of the aquifer.
Erosion/ flood control	Regulating	Groundwater aids in the control of erosion and in ameliorating the effects of flood by absorbing runoff. In addition, groundwater indirectly regulates soil erosion by providing water required by the vegetation cover.
Base flow	Regulating	Base flow derived from groundwater discharge is a fundamental service in many areas where springs and the dry-season flow depend heavily on groundwater. Base flow controls factors governing the extent of wetlands and surface vegetation types.
Flora/fauna habitats (biodiversity)	Regulating	There are numerous flora and fauna habitats that depend in part or entirely upon groundwater. Biodiversity issues generally relate to the regions where aquifers discharge through

		rivers, lakes or swamps. These areas form critical wildlife habitats and serve as sources of food, fuel and timber.
Soil formation	Supporting	The top layer of the Earth's terrestrial surface is shaped by the soil, containing unconsolidated rock and mineral particles mixed with organic material. Soil formation is influenced by different groundwater bodies and the type of geology.
Nutrient cycling	Supporting	Nutrients are one of the services provided by groundwater and subsurface aquifers play a role in the nutrient cycle through the storage, recycling, processing and acquisition of nutrients. For example, subsurface microorganisms recycle nutrients that are important in secondary productivity.
Recreation/ tourism	Cultural	Local communities and visitors often choose where to spend their leisure time based in part on the characteristics of the natural or cultivated landscapes in a particular area.
Aesthetic beauty	Cultural	Many people find beauty or aesthetic value in various aspects of groundwater dependent ecosystems, as reflected in the popularity of parks, scenic drives, and the selection of housing locations.
Education/ research	Cultural	Groundwater offers diverse opportunities for education and research in the context of social, economic and ecological issues.

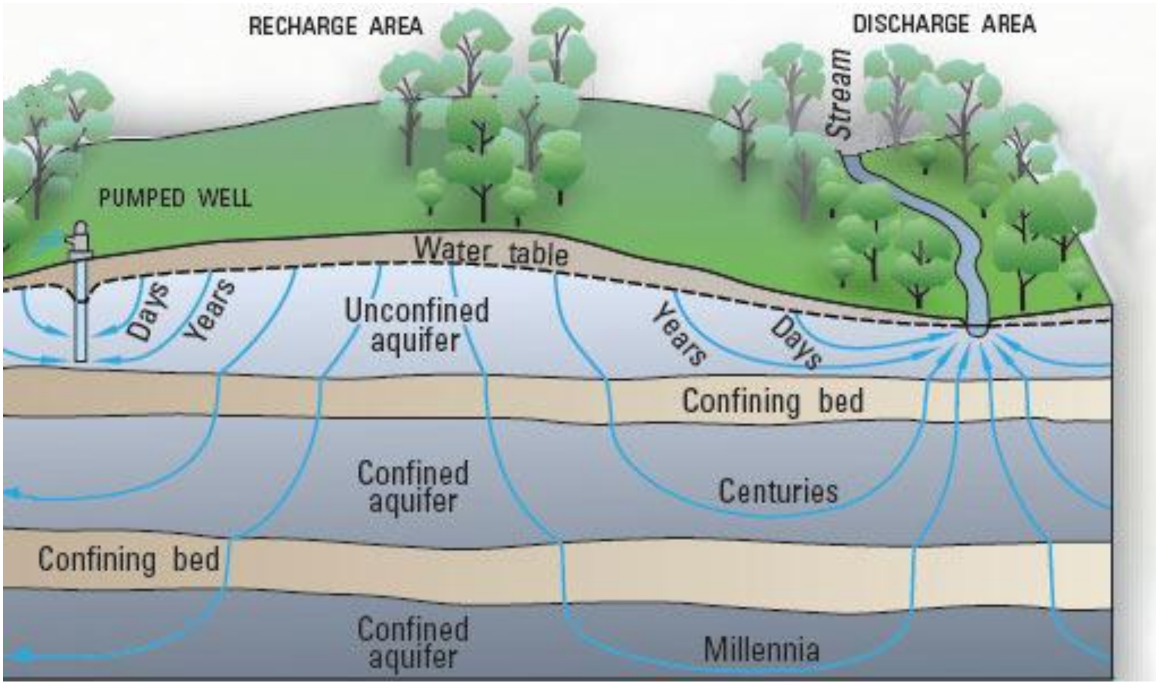
In order to understand the benefits of GESs for human well-being, it is necessary to consider the underlying hydro-geological characteristics of the resource base, the linkages between human well-being and ecosystem services, and the emerging trade-offs resulting from the overuse of some services and the disregard of the negative impacts upon other services.

2.1.1 Hydro-geological characteristics of groundwater

Groundwater differs considerably from surface water due to the contrasting physical and chemical environments in which it occurs. In a hydro-geological sense, groundwater is the water that occurs below the water table in the saturated zone in aquifers (extractable) and in aquitards (non-extractable).

According to Tuinhof et al. (2003), the management of groundwater is afflicted with many uncertainties and unknown variables: flow boundaries are difficult to define and may vary over time, it forms the 'invisible part' of the hydrological cycle, water resource managers and many water users have limited backgrounds in hydro-geology and little understanding of the processes induced by pumping water from an aquifer.

Aquifers themselves are naturally replenished by surface water from precipitation, streams and rivers when this recharge reaches the water table. Groundwater can provide a long-term reservoir of the natural water cycle, with residence times from days to millennia, as opposed to short-term water reservoirs such as the atmosphere and surface water (e.g., rivers, lakes), which often have a residence time ranging from minutes to years. **Figure 3** depicts an overview on the depth of groundwater and the relative groundwater travel times.



(source: http://ga.water.usgs.gov)

Figure 3 Qualitative flow times through a typical aquifer

All aquifers have two fundamental characteristics: (i) capacity for water storage and (ii) capacity for water flow, while the geological formations and spatial extent vary widely in the degree to which they exhibit these properties. According to Foster et al. (2006), the most significant elements of hydro-geological diversity can be summarized under the following two headings:

- major variation of aquifer unit storage capacity (storativity), between unconsolidated granular sediments and highly-consolidated fractured rocks,
- wide variation in aquifer saturated thickness between different depositional types, resulting in a large range in the groundwater flow potential (transmissivity).

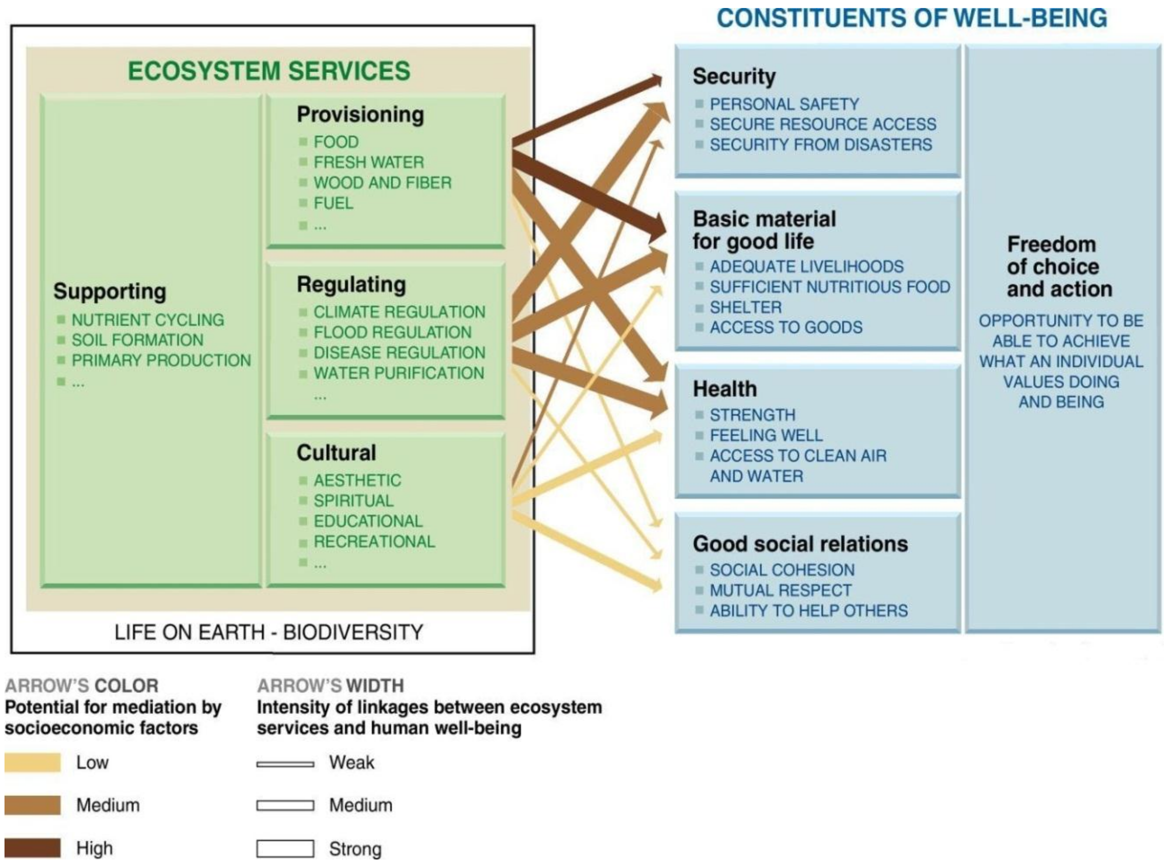
Due to its specific flow and storage characteristics, groundwater plays an integral part in maintaining different types of aquatic, terrestrial and coastal zones, and the associated landscapes, ecosystems and the services they provide.
The complex nature of groundwater is exacerbated by the pollution context and quality problems, with great variations in the chemical characteristics of aquifer materials and in the way pollutants react with them (e.g., pollutants may be filtered out mechanically or through adsorption onto particles within the soil or aquifer, or pollutants may remain mobile and the aquifer can become contaminated). Given the hundreds of thousands of naturally occurring compounds in groundwater and aquifer materials, and the similarly large number of compounds present in waste water released into aquifers, understanding and managing pollution is a highly complex task (Burke and Moench 2000).

2.1.2 Human well-being and ecosystem services

The MA (2005) found that the key components of human well-being include the basic material needs for a good life, the experience of freedom, health, personal security, and good social relations. It further stated that the interplay between these components provides the conditions for physical, social, psychological and spiritual fulfillment. Accordingly, ecosystems are essential for human well-being through their provisioning, regulating, cultural and supporting services (MA 2005), although often these are not initially apparent to resource managers and consumers. **Figure 4** illustrates the links between ecosystem services and human well-being, including indications of the extent to which it is possible for socio-economic factors to mediate the linkage (MA 2005). For example, where it is possible to purchase a substitute for a degraded service, the potential for mediation is high.

As ecosystem services are inextricably linked to human well-being, they are in turn impacted upon by human activities, which continue to intensify sharply with a corresponding increase in the pressure exerted on the Earth's resources and on the planet's capacity to deal with change. The MA (2005) identified direct and indirect pathways between ecosystem changes and human well-being, with the indirect effects generally characterized by more complex webs of causation, including social, economic and political threads.
Healthy aquifers and good quality groundwater deliver important (but often under-appreciated) services to society (Danielopol and Griebler 2008, Foster et al. 2006). In many countries groundwater extraction has increased exponentially with the spread of automated pumping technologies

and today, with a global withdrawal rate of 600-700 km³ per year, groundwater is the most intensively extracted raw material in the world (Vrba and Lipponen 2007).



(source: MA 2005)

Figure 4 Links between ecosystem services and human well-being

GESs provide a set of contributing factors for human well-being and basic human needs (Winkler 2006, Boyd and Banzhaf 2007). For decades, many authors have highlighted the manifold nature of the benefits people obtain from groundwater use (Llamas and Custodio 2003a). The main advantages can be summarized as follows: easy accessibility, great area-wide distribution, low capital intensity, relatively low cost, availability of technologies, widespread use by a large number of users, relative resilience to droughts, generally good chemical quality of water, large storage volume and unique opportunities for human development in poor regions (Tuinhof et al. 2003, Llamas and Custodio 2003b, Shah et al. 2000).

Due to advances in drilling and pumping technologies, and the development of hydro-geological research (Garrido et al. 2005), groundwater is now commonly used for irrigation and other industrial uses all over the world, it constitutes a relatively safe source of drinking water, and it has served to improve standards of living and socio-economic development.

However, the intensive use of groundwater is having a significant effect on aquifer conditions, including a decrease in water quantity and quality (Llamas and Custodio 2003a). The bulk of the damage has occurred over the last fifty years. Unlike surface water systems, much of this loss is irreversible and, therefore, much more critical. Additionally, groundwater planning and development has occurred with little appreciation of how societies and economies organize themselves to take advantage of the opportunities groundwater presents and to respond to management needs as they emerge (Burke and Moench 2000).

2.1.3 Trade-offs

Different ecosystem services are not independent of one another and the relationships between them may be highly non-linear (Rodríguez et al. 2006). The use of certain services often results in substantial declines in the provision of other services; in other words, they are traded-off (Holling and Meffe, 1996). An overly narrow focus on a limited set of ecosystem services may lead to ecological shifts with sudden losses of ecosystem services (Bennett et al. 2009). Trade-offs often arise from management choices made by humans, which can change the magnitude and mixture of the services provided by ecosystems (Rodríguez et al. 2006). If natural resource managers do not acknowledge trade-offs, it is likely to impair the effectiveness of any response policy for their management.

Besides direct management choices, further concerns relate to the environmental impacts of global change (e.g., extreme climate events, population growth, economic development), which increase social vulnerability and affect resilience in the face of change by altering the supply of ecosystem services and trade-offs (Rechkemmer and von Falkenhayn 2009).

Managing multiple bundles of ecosystem services simultaneously is crucial and at the same time extremely challenging (Bennett et al. 2009). Unintentional trade-offs occur when (i) management ignores the interactions between ecosystem services, (ii) knowledge and understanding of how they work is incorrect or incomplete, and (iii) when there are no specific markets for the ecosystem services in question (Rodríguez et al. 2006). To better understand and analyze ecosystem service trade-offs, Rodríguez et al. (2006) classified them along three axes:

Trade-offs in space: this refers to whether the effects and impacts of the trade-offs are felt locally or at a distant location – where decisions concerning trade-offs must take into account the possible implications beyond political boundaries,

Trade-offs in time: this refers to whether the effects and impacts of the trade-offs take place relatively rapidly or slowly – slowly changing factors are rarely quantified and difficult to monitor, consequently they are not perceived to be responsive to policy interventions,
Reversibility: this expresses the likelihood that the disrupted ecosystem service may return to its original state if the disturbance ceases – this is related to the resilience of the respective ecosystem.

The authors of the MA (2005) deduced from explorative scenario research that trade-offs are complex and often management decisions are responsible for ecosystem service trade-offs. They stated that irrespective of whether trade-offs affect nearby, faraway or future services, they usually involve unanticipated effects on secondary services.
Important specific groundwater-related trade-offs are those between agricultural production and water quality, land use and biodiversity, water use and aquatic biodiversity, as well as current water use for irrigation and future agricultural production (MA 2005). The points of competition over GESs are not always obvious and may only become apparent when exploitation has exhausted the capacity of aquifers to support current and future basic human needs and economic requirements. The environmental consequences of intensive groundwater exploitation include a lowering of groundwater tables in the long-term, which leads to a decoupling of groundwater and surface water systems, including a reduced transfer of groundwater to rivers, wetlands and springs (Bromley et al. 2001).
Danielopol et al. (2003) stated that the critical reduction in the volume of available groundwater reserves coupled to the permanent increase in the demand for water will be one of the major environmental trends of the next 25 years. According to climate scenarios developed by Döll and Flörke (2005), dramatic decreases in groundwater recharge are projected for, for example, Brazil, southwest Africa, Australia, and along the southern rim of the Mediterranean Sea by the end of 2050.
Apparently, there are no panaceas with regard to managing trade-offs because they are always related to space, time and the cultural aspects of certain societies (Hein et al. 2006), but one can state without any doubt that today's decisions regarding trade-offs will have an enormous impact on the state of future ecosystem services (Carpenter et al. 2006).

2.2 The challenge: Sustainable groundwater management

Ensuring sustainability with respect to groundwater poses a number of challenges. Not least of these challenges is how to interpret the concept of sustainability – an issue that appears to be poorly understood as far as groundwater is concerned. Various international agencies and programs have looked at ways and approaches to promote groundwater sustainability, including studies of how over-exploited aquifers, falling water tables, and seawater contamination threaten the world's underground reservoirs, upon which two billion people depend for their supply of drinking water and for irrigation purposes (UNEP 2003).

Groundwater sustainability is often simply expressed in terms of the relationship between aquifer recharge and discharge, and implies the stable availability of the resource for present and future generations. Equating groundwater sustainability with average annual recharge is unsatisfactory, however. Seward et al. (2006) argued that it is conceptually incorrect to define sustainability (or safe yield) on the basis of average annual recharge and to assume that recharge minus a reserve (aquatic ecosystem requirements and basic human needs) provides an amount of groundwater that can be sustainably allocated.

In this thesis, groundwater sustainability is perceived as being an interdisciplinary and comprehensive concept revolving around the complex interdependence of groundwater resources and the services they provide, the environment and the society. According to the Council of Canadian Academies (2009), groundwater sustainability encompasses five related goals:

(1) Protection of groundwater supplies from depletion: sustainability requires that withdrawals can be maintained indefinitely without creating significant long-term declines in regional water levels.
(2) Protection of groundwater qualities from contamination: sustainability requires that groundwater quality is not compromised by significant degradation of its chemical or biological characteristics.
(3) Protection of ecosystem viability: sustainability requires that withdrawals do not significantly impinge upon the contribution of groundwater to surface water supplies and the support of ecosystems.
(4) Achievement of economic and social well-being: sustainability requires that the allocation of groundwater maximizes its potential contribution to social well-being (interpreted to reflect both economic and non-economic values).
(5) Application of good governance: sustainability requires that decisions as to groundwater use are made transparently through informed public participation and with full account taken of ecosystem needs, intergenerational equity and the precautionary principle.

Underpinned by this thesis is the fact that groundwater management – especially in regard of the fifth goal – lacks the incentives necessary to prompt intervention and a change towards sustainable resource development. Calls for change in groundwater regimes usually arise only after a decline in well yields is observed or once the water quality is affecting stakeholders and indispensable services have been put at risk (Tuinhof et al. 2003). Changes to aquifers are often considered too late by those responsible for management to successfully bring about a recovery or to avoid major damage. To achieve long-term sustainability, governance must perceive groundwater and the services it provides as being an integral part of the SESs outlined in the following chapter.

2.2.1 Managing social-ecological systems in the groundwater context

To define a system as an SES it is necessary to describe the structure and pattern of the relations between the system's elements, in which networks, feedbacks and causal chains are concepts that can be expressions of these relations and dynamics (Jahn et al. 2009). This thesis builds upon the definition of SESs provided by Glaser et al. (2008), under which an SES consists of a bio-geo-physical unit and its associated social actors and institutions. Further, SESs are described as being complex and adaptive systems delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context.

Managing natural resources in a sustainable, equal and efficient manner requires integrated perspectives on social and ecological systems: a coupled, inseparable system of humans and nature (Folke et al. 2005, MA 2005), in which ecosystem services are conceived as a bridging component (Bennett et al. 2009). Hence, the dependence of social development and economic growth on ecological life-support systems is evident where communities benefit directly from ecosystems and their services in terms of food production and other products needed to support their livelihoods (Gómez-Baggethun and de Groot 2010).

Adaptive management approaches must take into consideration the fact that groundwater resources are part of the SESs influenced by many internal or external factors. A groundwater system has two dimensions, namely hydro-geological characteristics (e.g., hydraulic conductivity, transmissivity, storativity) and socio-economic characteristics (people and industrial sectors and their dependence on the physical environment) that are embedded in the overall political and legislative context that describes user rights and the protection of the resource (Burke and Moench 2000).

2.2.2 Challenges facing groundwater governance

According to Biswas and Tortajada (2010), radical changes in the governance processes and the institutions responsible for water are required if they are to cope with the immediate challenges, potential future changes and uncertainties. The authors concluded that these changes and uncertainties are related to a variety of factors including deeper and accelerating global integration, increasing free trade, higher levels of education, rapid scientific and technological developments in nearly all fields, revolutions in information and communication technologies, institutional innovations, growing demographic diversity within countries and between countries, incessant pressures exerted by economic, social and political dynamism, changing climatic conditions, and environmental crises and hazards.

The governance of natural resources has gone through a period of massive change in many countries and can be meaningfully examined from the broader perspective of the governance of SESs.
It is rare to find linear causal patterns in the linkages between SESs - ecosystem services - human well-being - human response - and feedbacks to drivers of change (Carpenter et al. 2009). In regard to groundwater, a reason might be that often the link between users and groundwater resources is not apparent and, because many benefits are public goods, the overall economic value of groundwater goes unrecognized (Burke and Moench 2000).
The shift in and degradation of groundwater has many complex causes, such as the dysfunction of institutions and policies, gaps in scientific knowledge, rigid bureaucratic hierarchies, unpredictable events and uncertainties (e.g., climate change). These management challenges are associated with failures of governance rather than with the actual resource base (Rogers and Hall 2003, Bakker et al. 2008). From a global perspective, Bergkamp and Cross (2002) divided the challenges facing groundwater governance into four categories: climate change, environmental, economic and socio-political challenges. The four categories and the respective challenges are shown in **table 3**.

Table 3 Main challenges facing groundwater governance

Climate change challenges
• Changes to the climate have a major impact on GESs, mainly the regulating services, which include long-term decline in groundwater storage, increased frequency and severity of groundwater droughts, increased frequency and severity of groundwater-related floods, mobilization of pollutants due to seasonally high water tables, and saline intrusion in costal aquifers due to sea level rise and resource reduction.
Environmental challenges
• Depletion can result in a loss of certain GESs, such as the processing of organic matter by diverse microbes and invertebrates.
• Intensive extraction may harm rare and endangered species restricted to very local habitats.
• Soil and groundwater contamination from industrial expansion and population growth is a concern and has long-term or irreversible environmental effects (e.g., chemical spills and

	leaching have a high residence time and relatively slow biodegradation rates in aquifers).
Economic challenges	
	• Depletion leads to higher costs due to the need for deeper drilling and pumping. • With an increasing global population, the demands placed on groundwater will continue to grow so as socio-economic needs can continue to be met. The resulting over-abstraction may result in decreased water availability leading to a reduced capacity for the irrigation of crops, thus compromising food security. • The removal of water in the underground area may cause the overlying substrata to collapse (e.g., Mexico City). • The remediation of polluted groundwater can be extremely expensive and is often ineffective.
Socio-political challenges	
	• Impacts on equitable access as a consequence of reduced groundwater availability. The poorer sectors of society are likely to be the hardest hit as they are most vulnerable to ecosystem changes. For example, declining water levels generally have large impacts in terms of equity, particularly in the developing world: wells dry up, forcing women and children to walk long distances or wait in line to obtain water. • Environmental health impacts are a further concern where poor quality water enters groundwater wells. • Transboundary groundwater problems including international agreements and conventions on water rights.

The research context and the challenges facing GESs outlined in this chapter shaped the basic conditions for the development of the research design, the analytical framework and the comparative analyses.

3. Conceptual research design

The research design underlying the study presented in this thesis builds upon different conceptual pillars put forward as realistic and promising approaches to deal with the complexity of groundwater management and ecosystem services. These concepts were chosen to conceptualize groundwater regimes across the whole range of social, economic, political and ecological issues.
A special focus was granted to the concepts and approaches of adaptive management and governance, the ecosystem services concept and institutions governing GESs.

As a new element to the conceptual research design, a set of criteria and indicators was developed to analyze vertical and horizontal integration structures. Furthermore, a framework to explore the role of institutions in GES management was established.

3.1 Adaptive groundwater management and governance

The concept of adaptive management has existed for quite some time in the context of resource management (Holling 1978, Walters 1986, Pahl-Wostl 1995, Lee 1999). The overall idea of adaptive management builds on the recognition that ecosystems are complex systems that are adaptive and self-organizing, and have to be managed in such a way that is possible to adjust to changes or unexpected occurrences (Gunderson and Holling 2001). As aquifer systems are complex, difficult to understand, and the consequences of human intervention are difficult to predict (Seward et al. 2006), adaptive management is a suitable approach to deal with these challenges.
The thesis builds upon the interpretation of adaptive management, defined by Pahl-Wostl et al. (2010, p. 573) as, "a systematic process for improving management policies and practices by systemic learning from the outcomes of implemented management strategies and by taking into account changes in external factors in a pro-active manner."
In addition, adaptive management accounts for uncertainties explicitly and requires a basic rethinking of what management means in an uncertain and changing environment comprising various complex systems (Pahl-Wostl et al. 2007).

Originally developed as a management concept for ecological systems, adaptive management has more recently evolved into an interdisciplinary field of research and action, as reflected in the broader term adaptive governance (Folke et al. 2005). Water management no longer deals only with complex ecological and technological systems; rather it has become a complex system itself, characterized by a diversity of social, economic and ecological elements.

This interpretation places a strong focus on the general need to increase the adaptive capacity of a management regime to deal with any kind of uncertainty and surprise. Adaptive capacity is described as “the ability of a resource governance system to first alter processes and if required convert structural elements as a response to experienced or expected changes in the societal or natural environment” (Pahl-Wostl 2009, p. 355).

Given the predominantly technocratic development of groundwater historically, most governance and management structures do not provide the structural conditions necessary to implement adaptive approaches without changing certain characteristics of a regime. For a shift in favor of the adaptive management of groundwater to occur, consideration of the following is necessary (adopted from Pahl-Wostl et al. 2008):

- → a shift towards participatory management and collaborative decision making,
- → greater integration of different research fields and interdisciplinary sectors,
- → decentralized and more flexible management approaches, which take uncertainties and unexpected events into account,
- → incorporation of ecological system properties and mainstream GESs into management goals at all levels (from local to international),
- → provision of free access to information and the conscious collection of data and monitoring of the state of GESs.

These pounts are crucial for the comparative analysis of vertical and horizontal integration.

3.1.1 Vertical and horizontal integration

The ability to implement adaptive governance and to integrate it within the overall management of groundwater resources depends on a number of structural regime characteristics (Pahl-Wostl et al. 2010). Vertical (hierarchical) and horizontal (sectoral) integration are considered to be essential characteristics of an adaptive regime (see **box 1**) (Pahl-Wostl 2009, Pahl-Wostl et al. 2010, Huntjens et al. 2010, Krysanova et al. 2010). Therefore, the comparative analysis will focus on the influence of vertical and horizontal integration on the effectiveness of groundwater regimes governing GESs. A high degree of integration is expected to (i) contribute to improving the quality of management by incorporating different kinds of knowledge and information about GESs, (ii) increase the acceptance of decisions and innovative approaches, and (iii) improve both compliance and implementation on the ground (Schenk et al. 2007).

Box 1 Vertical and horizontal integration and their importance for adaptive groundwater governance

Vertical integration refers to the connectivity and interplay of various levels in a hierarchical political system. The distribution of groundwater management between a top-down and a bottom-up regime implies that decision-making authorities do not reside at a single level, neither at the top (highest level of government enforcing decisions), intermediate (state or provinces enforcing decisions beneficial for their regions) nor at the individual level, with complete freedom to act or being connected solely within market structures (Pahl-Wostl 2009).

- → A lack of vertical integration leads to policy failures due to the disconnect between management levels and, as a consequence, causes the gap between policy processes and operational implementation to widen (see Ostrom 2005, Irwin and Ranganathan 2008, Pahl-Wostl 2009).
- → The sustainable management of GESs depends on the decisions of various actors, each with individual goals and values attributed to GESs; sustainable groundwater management requires, among other things, a broad integration of different stakeholders, both state and non-state actors.

Horizontal integration refers to sectoral integration between groundwater-related sectors such as agriculture, forestry, tourism, fisheries, municipal supply and conservation to name just a few.

- → Highly fragmented management structures erect barriers to successful groundwater management and implementation, whereas sectoral integration anticipates emergent problems, resolves conflicts and coordinates policy implementation (see Huntjens et al. 2010, Pahl-Wostl et al. 2010).

Relatively little is known about the relationship between adaptive regime characteristics, such as vertical and horizontal integration, and their effects on the performance of groundwater management. In order to determine the degree of vertical and horizontal integration and its potential impacts on the management of GESs, the research built upon a set of criteria used to investigate the state of integration (**table 4**). Each criterion incorporates one or more indicators assumed to improve the quality of sustainable groundwater management.

Table 4 Research framework: vertical and horizontal integration

Integration dimension	Criterion	Indicators	Impacts on the management of GESs
Vertical integration	Multi-level interactions	• Groundwater management is shaped jointly at different levels with coordination and responsibilities at different levels • Actors operate at multiple levels of policy and management processes	→ Decentralized decisions regarding GESs take into account different GESs rather than single services → Effective and fast responses to ecosystem risks at multiple levels
	Stakeholder participation	• Non-state actors are involved in management processes and set up rules that directly affect them	→ Incorporation of essential perspectives and local knowledge of GESs → Improved quality and implementation of plans and projects, and greater compliance with different rules
Horizontal integration	Sectoral integration and cooperation	• Actors from different sectors are involved in decision-making	→ Enhanced economic collaboration → Consideration of GESs lacking a specific economic market

A detailed description of how vertical and horizontal integration were operationalized is provided in **chapter 4.3.3**.

3.2 The ecosystem services concept

The concept of ecosystem services is an ecologically based management approach and serves as a concept bridging social and ecological systems (see Daily 1997, MA 2005, Brauman et al. 2007, Loring et al. 2008). This concept provides a strategy for the integrated management of land, water and living resources that promotes sustainable use and conservation in an equitable way (MA 2005).

The ecosystem services concept integrates SESs in an attempt to explain the effects of human policies and actions on natural systems and on human well-being (Foster et al. 2003, Farber et al. 2006). A benchmark definition of ecosystem services research was provided by the MA, which constitutes an international scientific effort (Brauman et al. 2007). The MA framework was developed within an internationally acknowledged study and designed to capture the manner in which groups of people interact with and rely on ecosystems, and how changes to these ecosystems influence individual and community well-being.

The authors of the MA categorized ecosystem services according to four classes: provisioning, regulating, supporting and cultural services. The four categories – including examples of GESs – were defined as follows:

- Provisioning services are '*products obtained from ecosystems*' (e.g., aquifer storage and retention for domestic, industrial and agriculture uses)
- Regulating services are '*benefits obtained from the regulation of ecosystem processes*' (e.g., water regulation, water purification and waste treatment, erosion regulation and flood control)
- Supporting services are '*services necessary for the production of all other ecosystem services*' (e.g., water and nutrient cycling)
- Cultural services are '*non-material benefits that people obtain from ecosystems*' (e.g., spiritual and religious values, recreation and aesthetic experiences).

This categorization serves as a functional abstraction from ecological resources to 'ecosystem services' that highlights the links and dependencies between these services and human well-being (Loring et al. 2008).

A key strength of the MA framework lies in the linkages between ecosystem services and components of human well-being such as security, health, social relations, life basics and freedom of choice and action (see **chapter 2.1.2**). The relationship between linkages may differ in various ecosystems, spatial structures, economies and subject to contrasting human behavior.

The overall challenge, according to Daily and Matson (2008), is how to make the ecosystem services approach operational, or in other words, what kind of transformation will be required to move from conceptual frameworks and theory to political and practical integration? Identified in the MA framework are five categories of responses facilitating the sustainability of ecosystem services:

- Measures concerning institutions and governance focus mainly on enabling the implementation of an ecosystem services approach in management structures.

- Economic measures such as subsidies, rewards for positive actions, penalizing measures for negative actions and payment for ecosystem services.
- Social and behavioral responses focus on the dissemination of information and on empowerment.
- Technological responses such as measures to increase the efficiency of the use of resources, to reduce the impacts of drivers, to provide alternatives for lost or impaired ecosystem services, and to develop monitoring and early warning systems to facilitate better management of ecosystem services.
- Knowledge and cognitive responses, namely gathering knowledge and ensuring the adequate application of information.

The ecosystem services framework not only renders complex linkages explicit, but also the trade-offs between ecosystem services and their users (see **chapter 2.1.3**).

3.3 Institutional approach

The last approach, the institutional approach refers to the responsiveness of institutions in groundwater management and their effectiveness within SESs. This includes how people respond to periods of change and how societies reorganize in response to this change in the context of natural resource management. The term institutional response to GESs describes the central behavioral tendencies of a regime and the social dynamics that result from different hydro-geological and environmental conditions. Institutional response is often induced by certain drivers of change, which either have the power to cause SESs to deteriorate into undesirable states or to trigger change towards more adaptive management, resulting in new forms of governance systems with the ability to manage dynamic ecosystems (Folke et al. 2005).
Institutional changes may have the power to shape incentives in human exchange and collaboration, and may also contain legal mechanisms to control people's rights to use the environment. Institutions can mediate the link between ecosystem services and the constituents and determinants of human well-being (MA 2005).

In order to analyze institutional response during periods of change, and to determine the effectiveness of institutions in relation to GESs, a framework that can incorporate institutions and ecosystem services in a holistic manner is required. Such a framework was developed as part of this study in order to highlight the role of institutions in groundwater ecosystem management (**figure 5**). The conceptual foundation of this framework builds upon the ecosystem services concept (see MA

2005), in which the linkages between ecosystem services and components of human well-being are integrated in an attempt to explain the effects of institutions on societal and natural systems (as explained in **chapter 3.2**). The framework combines a reciprocal approach in which humans create institutions and use them when they interact on the one hand (Ostrom 2008) and in which human behavior and interactions are influenced by existing institutions on the other (Young 2002).

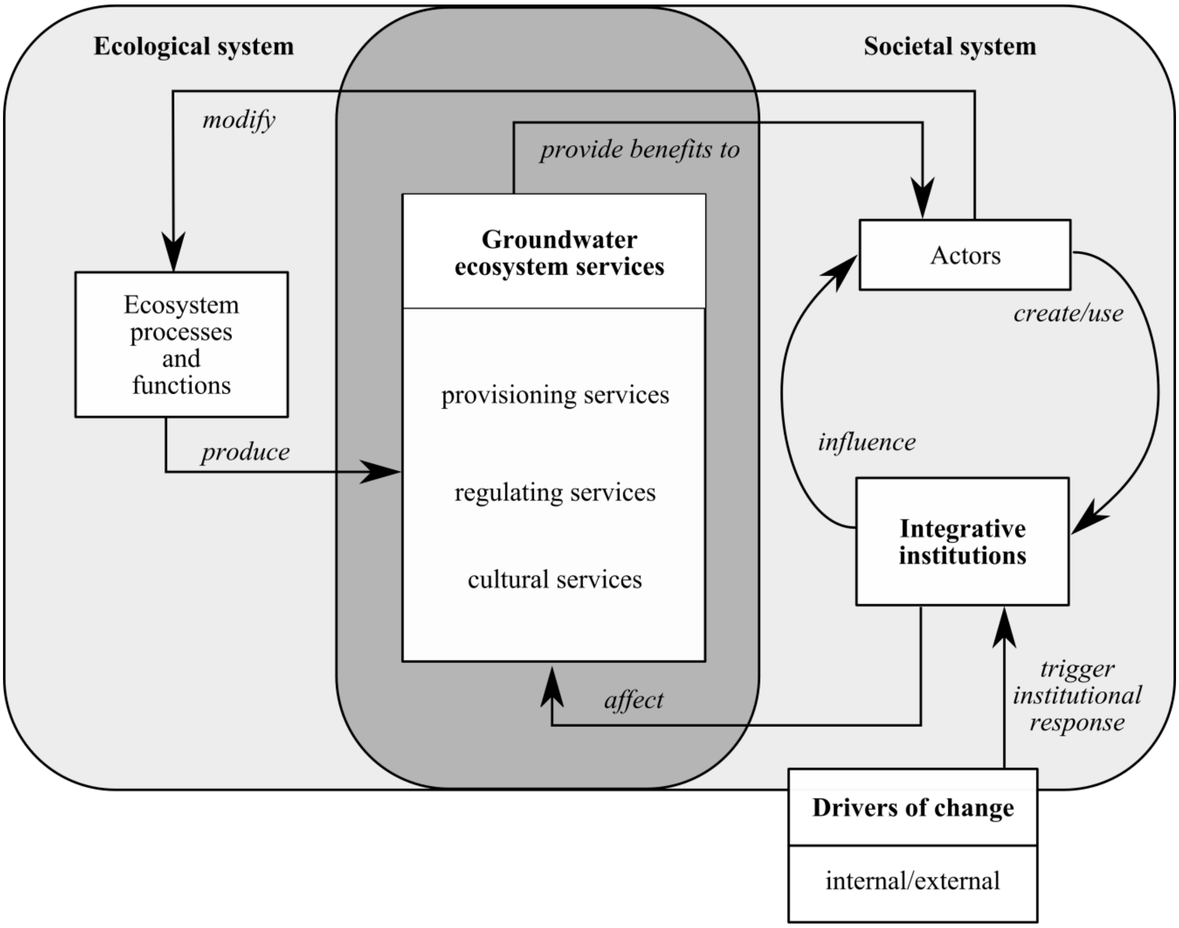


Figure 5 Conceptual framework: the role of institutions nested in social-ecological systems

This framework allows the exploration of the institutional response across case studies in two steps: (i) the analysis of internal and external drivers of change influencing institutional response and (ii) the effectiveness and integrative perspectives of institutions with respect to GESs. The distinction between internal and external drivers of change provides an opportunity to include highly diverse types of drivers crucial to explaining the role of responses in describing, understanding and projecting changes in groundwater resources, ecosystem services and human well-being.

On the one hand it is argued that institutions have the power to shape incentives in human exchange and collaboration, and contain mechanisms to control people's rights to use the environ-

ment. Further, they mediate the link between ecosystem services and the constituents and determinants of human well-being (MA 2005). Therefore, they link society to nature, and govern SESs in a complementary way, aspiring to long-term objectives (Hanna et al. 1996, Gómez-Baggethun and Kelemen 2008). On the other hand, institutional constraints might limit the applicability and effectiveness of adaptive management and, as stated by Lee (1993), institutional rigidity presents a possible barrier to the successful application of an adaptive management approach.
Creating, revising and modifying institutions is a social process requiring the knowledge and active involvement of groundwater stakeholders and official state departments from different levels.

3.4 Summation of the conceptual approaches

The three research approaches presented here are strong in terms of their usefulness as a means to analyze the complexity and individual context-dependent dynamics of a groundwater regime. Further, they facilitate the bridging of the social and natural science disciplines. Summarized in **box 2** are the key aspects of the three concepts.

Box 2 Key aspects of the conceptual research approaches

Adaptive management & governance

- Recognition of the fact that ecosystems are complex systems capable of adaptation and self-organisation
- Consideration of uncertainties and changing environments
- Increased adaptive capacity of a management regime to deal with uncertainty and surprise
- Integration of vertical and horizontal integration as essential components of groundwater regimes

Ecosystem services concept

- Bridges social and ecological systems in which ecosystem services frame the bridging element of SESs
- Integrated strategy for the management of land, water and living resources
- Highlights the linkages between ecosystem services and human well-being

Institutional approach

- Description of the central behavioural tendencies of a governance regime and the contextual social dynamics
- Has the power to shape incentives in human exchange and collaboration, and contains mechanisms to control people's rights to use the environment
- Mediation of the link between ecosystem services and the constituents and determinants of human well-being

4. Methods

In this chapter the main research methods used in this study are discussed. Relying solely on statistical and quantitative analytical results to explore and compare case studies may prove insufficient as a means to understand highly complex SESs, groundwater regimes and the specific context of a case study. For this study an integrated approach was applied, including expert interviews and a literature review to provide a comprehensive procedure to reveal the entire story behind a case study.

The greater part of **chapter 4** corresponds with the content of research topic 1, as published in paper 1.

4.1 The case study research method

The research presented is based upon three case studies – the Sandveld (South Africa), the UGB (Spain) and the Spree Basin (Germany). The analysis focuses on the perspective of the interviewees with respect to groundwater regimes and GESs (see **chapter 4.3.2**).

In order to achieve the level of accuracy required to answer the research questions, a small number of detailed case studies was chosen.

Although the insights and results gained from case study research may not be entirely generalizable, they contribute to the accumulation of scientific knowledge and facilitate learning processes due to the context-dependent knowledge produced. Further, the results constitute a basis for future research and additional case study comparison. Hence, the case study research method supports an understanding of a complex issue or object, and widens experience and underlines that which is already known about the case study and from previous research. In other words, "a case study research method is an empirical inquiry that (i) investigates a contemporary phenomenon within its real-life context; especially when (ii) the boundaries between phenomenon and context are not clearly evident; and (iii) in which multiple sources of evidence are used" (Yin 1994, p. 23). An inherent characteristic of the case study method is that it operates with a severely restricted research focus. One of the prime reasons for restricting the scope of the research is that it facilitates the construction of a detailed, in-depth understanding of that which is being investigated.

The case study approach contains qualitative research methods for the examination of contemporary real-life situations and provides a basis for the application of diverse methods. The justification for the choice of the qualitative perspective, as compared to a quantitative strategy, is based on the research questions posed. The research questions posed in this study focus to a large extent on

the perceptions, meanings and understandings of individuals in relation to their experience and beliefs in the field of groundwater management. In addition, qualitative research was preferred because it delves into system complexities and processes in-depth, by exploring where and why certain management approaches and policies are chosen, and how they influence GESs.
Case study research is not defined by any particular technique for either data collection or analysis. Rather the method involves multiple sources and combinations in the data collection process. Given that the contribution made by case study research depends on an intensive engagement with the case itself, the researcher must be competent using several data collection techniques (Poteete et al. 2010). The methods used in this study were face-to-face interviews, questionnaires and the analysis of documentary materials.

Case study research requires a large amount of data and information. This necessitates the systematic organization of the data collated so that the researcher is not overwhelmed by the amount of data and does not lose sight of the original research purpose and questions.
The overall contribution of case study research to theory development depends essentially on the ability of scholars to overcome barriers to the exchange of the findings and results that arise from disciplinary divisions (Poteete et al. 2010). The case study research method was considered extremely attractive in this context because it requires relatively few assumptions about the nature of data or the underlying causalities in natural resource management (Mahoney and Goertz 2006, Munck 2004). The intensive exploration of various cases often reveals multi-stranded relationships and unanticipated patterns that set limits to the generalization and simplistic comparability of diverse case studies (Mahoney 2003, Gerring 2004, Rogowski 2004).

The goal of this study was less to generalize between the case studies in South Africa, Spain and Germany and other case studies but rather to represent, through the selected case studies, critical and unique circumstances for groundwater ecosystem management in the respective study. The comparison of case studies is, therefore, a validation of theory on the basis of testing characteristics assumed to be crucial for adaptive groundwater regimes (outlined in **chapter 3**). On the basis of the criteria and indicators depicted in **table 4**, it is possible to detect a certain degree of generality in order to contribute to existing theories and concepts pertaining to adaptive management and the ecosystem services approach.
According to Poteete et al. (2010), the most important impediment to the contribution of case study research to theory building, however, is the difficulty synthesizing case study results, especially if the researcher is to recognize patterns across case studies. As a reference point to detect patterns of adaptive groundwater regimes, the approach adopted here was to build upon a framework suitable

for use in the analysis of results from different case studies in a systematic fashion, thereby facilitating comparison of the results obtained from different case studies.

4.2 Framework objectives and requirements

Current groundwater ecosystem management lacks new approaches and frameworks necessary to deal with system complexity. The use and the planning of the management of groundwater resources are based mainly on certain specific predictions about aquifer characteristics and behavior, such as recharge potential, water consumption and quality aspects. However, in complex SESs in which the connections and interplay between human well-being and ecosystems are continuously changing, the management often fails to what the consequences of human actions will be. Hence, management should not be viewed as an isolated solution to a certain problem; rather the management of natural resources should be understood as an experimental learning process (Carpenter et al. 2006).

In order to address these issues an analytical framework that captures system complexities and feedbacks between the social and the ecological dimension is needed. This analytical framework must support the development of a knowledge base that enhances scientific understanding, thereby improving groundwater ecosystem management and supporting changes towards more adaptive management approaches. Requirements identified as being important while designing this coherent framework should (adopted from Pahl-Wostl et al. 2008):

→ be open to the incorporation of different scientific concepts and world views concerning groundwater ecosystem management governing GESs (such as adaptive management and the ecosystem services approach),

→ include and address different types of local knowledge and stakeholder perspectives, those of farmers, conservationists, municipalities, industry and so on,

→ be able to handle different types of data and information (e.g., about ecosystem services, aquifer systems, climate conditions, the actors involved, management behavior etc.),

→ consider multiple levels and temporal scales of GESs and the corresponding management level (both natural and administrative boundaries),

→ provide a comprehensive analytical approach to investigate linkages between management and GESs (e.g., via institutions).

These requirements served as a guiding principle during the development of an analytical framework that built upon the MTF (section 4.3). The last point was especially important for the analysis carried out as part of this study. The following sections provide insights into how these linkages were investigated.

4.3 The management and transition framework

The MTF is an interdisciplinary conceptual and methodological framework supporting the analysis of water systems, management processes and multi-level governance regimes. On the one hand it serves to improve the scientific understanding of system properties while at the same time providing practical guidance for the implementation of transition processes towards more adaptive systems (Pahl-Wostl 2009, Pahl-Wostl et al. 2010). The MTF was developed by Pahl-Wostl and colleagues at the Institute of Environmental Systems Research at the University of Osnabrück. The framework was a major outcome of the NeWater project (‘New Approaches to Adaptive Water Management under Uncertainty’) financed by the EU’s 6th Framework Program in the field of adaptive management.

The conceptual foundation of the framework can be summarized under the overall thematic areas adaptive management and characteristics of adaptive water governance (Holling and Gunderson 2001, Folke et al. 2005, Pahl-Wostl 2009, Knüppe and Pahl-Wostl 2011), social learning and regime transitions (Pahl-Wostl et al. 2007, Pahl-Wostl 2009), and the institutional analysis and development framework (Ostrom 2005) to analyze collective choice processes from an institutional perspective.

For the research presented in this thesis, the framework was amended with regard to the conceptual approaches introduced in **chapter 3**.

The framework offers a modular structure and can be adjusted to those aspects that are of interest; for example, with regard to groundwater ecosystem governance and management processes, physical characteristics of the environment or societal conditions. Hence, certain elements of the original framework were modified in order to analyze groundwater regimes and GESs.

A major advantage of the MTF is that it can support flexible and context-sensitive analyses without being restricted to specific case studies. It is possible to compare different water management cases embedded in different social, ecological and economic contexts. A further advantage is the possibility to address subject matters such as groundwater allocation, water quality and quantity, flood protection, and aquatic ecosystem health.

The framework consists of two main components, namely the class diagram and the policy cycle, which will be introduced in the following.

4.3.1 The class diagram

The structure of the MTF provides an ontology and formalized representations of a set of several class elements. Classes are defined here as different elements and their relationships, attributes and applicable methods that have been identified as being essential in order to describe water management processes and structures (Pahl-Wostl et al. 2010). Every single class has specific characteristics, but meaningful conclusions about management dynamics cannot be made until single classes are linked to one another and frame a holistic system of processes, structures and feedbacks. Depicted in **figure 6** is a simplified illustration of the classes and their linkages (Knüppe and Pahl-Wostl 2011). The original structure of the MTF class diagram, including the attributes, can be found in **appendix A**. **Table 13** in **appendix B** presents all of the classes, further explanations and the corresponding attributes.

In order to simplify the illustration, attributes of the classes are not shown. Special emphasis is placed on *action situations* (right side) governing the *water system* and its components (left side). A diamond denotes the fact that an aggregation '*has a*' link; e.g., a *water system* has one (or more) *ecological systems,* which in turn have one (or more) *GESs*. The broken line denotes relationships between *action situations* and an *outcome* as well as between an *outcome* and a *water system*.
The choice of the level of detail and the amount of data for each class element and their attributes depends on the degree of information that is required to understand and analyze a certain research issue, and to answer various questions, which allows scholars a high level of freedom.

In the following the classes are described. The *water system* (e.g., Upper Guadiana Basin) is the highest and most aggregated class, and comprises all environmental and human components of which the *societal* and *ecological systems* are parts. The *societal system* is shaped by political, historical, legal and cultural context-specific circumstances. In general, *societal systems* refer to national or regional boundaries such as states or provinces as many of the attributes characterizing the context are determined by and for administrative boundaries (e.g., legislation, economic growth). The *ecological system* comprises abiotic and biotic components of the groundwater body and related ecosystems such as floodplains, swamps, springs and sloughs as well as subterranean ecosystems and fauna. *GESs* frame the interface and the bridging part of *societal* and *ecological systems* and provide benefits for human well-being.

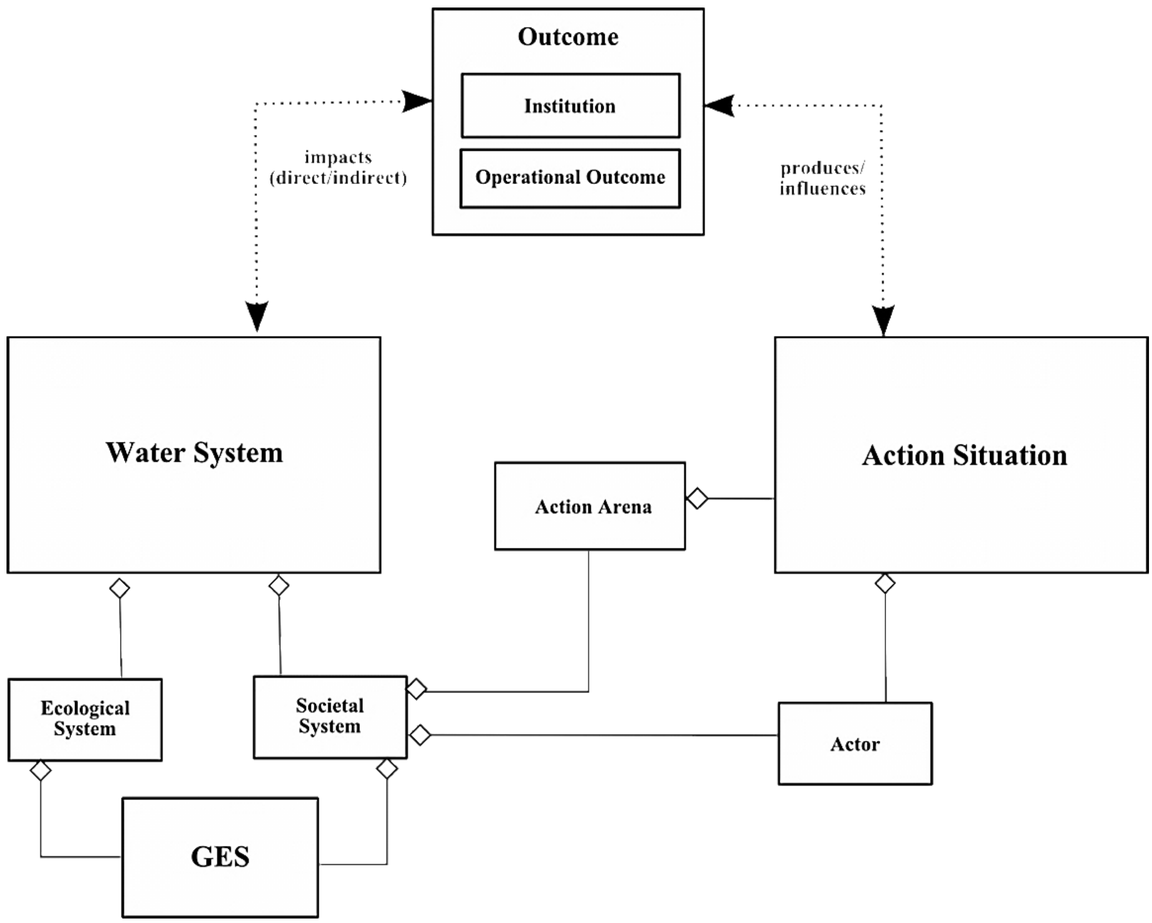


Figure 6 Framework of class elements and their connections

An *action arena* (AA) specifies the political context of groundwater management more precisely. *AAs* are represented by *action situations* (AS) or *actors*. Predefined *AAs* exist: water supply, flood protection, drought prevention, water pollution control, fisheries, agriculture, energy, tourism, spatial planning, nature protection and water ecosystem management. An *AS* maps a structured social interaction context of policy and management processes embedded in governance systems that are shaped by different *actors* at different levels, and their interaction between one another. According to Ostrom's definition, an AS is constituted whenever two or more actors are faced with a set of potential actions that jointly produce an outcome (Ostrom 2005). Here, *outcome* is linked to either new *institutions* or *operational outcome*. The first are considered to be a set of rules, decision making procedures and programs that define social practices, assign roles to the participants in these practices, and guide interactions between the occupants of individual roles (Young 2002). *Operational outcome* constitutes measurable effects impacting upon *societal* and *ecological systems* (e.g., land use change, composition of water chemistry, a fall in the groundwater table).

4.3.2 Data collection and analysis

Data collection was based on intensive document research (study of legal documents, publications on laws and regulations, research reports and peer reviewed articles) and a series of expert interviews carried out during field work in South Africa, Spain and Germany in the years 2009-2011. In each case study, the number of interviewees ranged between 18-22 experts and the interviews varied from 1-3 hours in duration. The interviewees were chosen based upon their specific knowledge and broad experience in the field of groundwater resources management. The experts reflected various types of expertise and knowledge: politics and administration, consulting, water supply, forestry, research and nature conservation. An overview of the sectors, organizations and agencies chosen for the interviews can be found in **appendix C**.
The interviewees were asked to outline a sequence of groundwater policy and management processes covering the past 20-25 years in order to help identify a transformation towards more adaptive management. These processes are represented by different ASs. After the identification of ASs, and of the corresponding information about actors and outcomes, appropriate aggregations of a sequence of ASs were assembled into meaningful management and policy processes. This aggregation was in turn discussed with case study experts and reinforced with the help of additional desktop research. The individual aggregation refers to various periods of groundwater management characterized by different drivers of change (e.g., political regime shift, ecological pressure).
Additionally, data collected through a set of semi-structured questionnaires supported a better understanding of the individual background of a case study, including the role of GESs and the corresponding management base at different hierarchical levels. This allowed the interviewer to obtain a deeper understanding of an individual's perception and experience by letting the interviewees focus on the issues they believe to be the most relevant.

4.3.3 The total system database and queries

In order to structure and analyze a huge amount of data (actors, management processes, institutions and outcomes) in a systematic fashion, a formalized database approach, the total system database (TSD) was used. The TSD serves as an underlying condition to compare the chosen case studies. The TSD was developed based on the MTF in order to translate the conceptual research design into an operational tool. Microsoft Office Access was chosen for the technical implementation of the TSD, to describe dynamic governance and management processes by considering the overall context in which these processes unfold in individual case studies (Knieper et al. 2010). Starting forms of each database were created containing consistent datasets and information to facilitate the de-

scription and representation of dynamic groundwater regimes and their respective geographic, ecological, political and societal contexts. These forms comprised relevant class elements (see **figure 6**), including their attributes and relationships. After data were input into the TSD forms, queries were designed to provide variables, used as a function to calculate one or more relationships within and between the classes. The queries facilitated an operationalization of the degree of vertical and horizontal integration represented by ASs and actors. For example, queries can be calculated to identify whether actors are active at multiple levels during management processes or whether the connectivity between levels within a certain management process is high or low. Apart from the demonstration of simple relationships between various class elements (e.g., institution impacts water system), the main objective was to conduct an in-depth analysis of the management interactions of actors and ASs (including linkages and feedbacks), and the outcomes of these interactions.
All of the relationships, basic system properties, networks of ASs and queries for the analysis of vertical and horizontal integration are summarized in **appendix D**.

Box 3 Summing up of the methodological and analytical procedures

A variety of different steps were carried out during the data collection period and the analysis, conducted in the following logical order:

- → General case study literature review with a particular emphasis on groundwater, ecosystem services and the respective political arena
- → Identification of general groundwater management processes (afterwards identified as ASs) and actors in the case studies based on a literature review
- → Conducting of stakeholder and expert interviews:
  - Awareness and role of GESs in the case study areas
  - Groundwater management; i.e., development of main ASs including the relationship between ASs and the overall impacts on GESs
- → Assembling and storage of data using the TSD
- → Application of various queries to the TSD
- → Qualitative analysis of queries
- → Underpinning of the outcome of the analysis with additional literature review
- → Overall comparative analysis of the three case studies

5. The case studies

The research was focused on three case studies in different geographic regions, which acted as reference points for the analysis: the Sandveld in South Africa, the UGB in central Spain and the Spree Basin in eastern Germany.

The chosen case studies represented excellent examples for the analysis of the challenges associated with groundwater governance and management performance. The comparative analysis allowed for the drawing out of similarities and differences between the three case studies. Each of the cases was characterized by groundwater systems highly modified by anthropogenic actions influencing the integrity of ecosystems and the provision of GESs.

The three case studies were also interesting from a governance point of view. Each went through periods of massive change, including shifts in integration structures and changing perceptions of the significance of GESs for ecological processes and functions.

Highlighted in **table 5** are key case study facts pertaining to the general water system, societal and ecological system and natural hazards.

Table 5 Key case study facts

System elements	Attributes	Case studies		
Water system		**Sandveld**	**UGB**	**Spree Basin**
	Basin area (km²)	4 590	16 000	10 100
	Precipitation (mm/a)	200	415	530
	Evapotranspiration (mm/a)	1 600	1 000	610
	Climate-moisture index	Semi-arid	Semi-arid	Sub-humid
Societal system		**Western Cape Province**	**Castilla-La Mancha**	**Brandenburg**
	Population density (inhabitants/km²)	< 20	25	30
	Economic sector	Agriculture	Agriculture	Lignite mining, fisheries, tourism
Ecological system		***Verlorenvlei* RAMSAR site**	***Las Tablas de Daimiel National Park* RAMSAR site**	***Spreewald* UNESCO Biosphere Reserve**
	Water availability	Low	Low	Medium
	Degree of human influence	High	High	High
Natural hazards		**Droughts**	**Droughts**	**Droughts, floods**
	Frequency-intensity distribution	Annual – during summer; the drought extent depends on rainfall during winter	Irregular – increasing tendency during summer	Regular droughts (summer) and irregular floods (mainly winter)

The analytical scale is associated with the sub-basin level, which constitutes the implementation level of most groundwater policy frameworks and institutions embedded in the overall national and international context of the respective case study.

5.1 Sandveld, Western Cape Province (South Africa)

The Sandveld consists of 4 590 km² of coastal plain along the west coast of South Africa, bordered by the Olifants River catchment to the north and east, the Berg River catchment to the south and the Atlantic Ocean coastline to the west (DWA 2005). The area features sandy and nutrient poor soils and comprises granular primary aquifers and deeper fractured rock secondary aquifers. The volume of the water stored in the Sandveld aquifer is estimated to be approximately 500 Mm³, which is recharged by the catchment area of the Cederberg mountain ranges to the east of the Sandveld region (Conrad et al. 2005). The region experiences dry summer and wet winter conditions, similar to other regions of the Western Cape. Although there have been no detectable trends in the mean annual rainfall since 1900, there has been a noticeable increase in the mean annual temperature (~ 1 C) (Archer et al. 2009).
The Sandveld is a rural area with extensive potato farming primarily under center-pivots, with a few towns, and fishing and tourism developments along the coast. Agriculture is the dominant employer in the Sandveld and potato production and processing is the main economic activity, complemented by some cereal and rooibos tea production (Franke et al. 2010). It was estimated that in the Sandveld region alone, potato production represents an annual turnover of approximately R500 to R700 million. The core of the agricultural production area coincides with sensitive aquatic and terrestrial ecosystems (e.g., the Cape Floristic Kingdom, Verlorenvlei RAMSAR site, Greater Cederberg Biodiversity Corridor). Determinations of ecological water requirements for the Sandveld indicate that unsustainable development of groundwater is impacting upon environmental flows and reducing the availability of diverse ecosystem services (Conrad et al. 2005). Moreover, irrigation enhances the leaching of agri-chemicals into groundwater reserves and many ecological habitats and landscapes are being threatened or fragmented due to land clearance for potato production.
Historically, the Sandveld received little attention in terms of economic development and ecological maintenance; hence the groundwater was used by individuals without coordinated groundwater management. During the last two decades, programs and measures were developed to better understand the quality and quantity of groundwater, geological formations, the storage capacity of aquifers, and the ecological integrity of the landscape water regime. To implement sustainable irrigation practices, abstraction must be regularly monitored, wells must be registered and licensed, hy-

dro-geological and climate data must be accessible for farmers, and a fair pricing system must be established. Although the area is receiving much attention due to its environmental uniqueness, and its significant groundwater resources, many challenges still remain for water and land managers: illegal agriculture activities, insufficient pivot irrigation systems, decreasing water quantities, increased water contamination and salt water intrusion along the coast. Over the last five years the industrial sector, the conservation sector and farmers have joined forces to address agricultural sustainability, conserve the remaining fragments of the biodiversity-rich land, and establish natural corridors connecting fragmented habitats.

5.2 Upper Guadiana Basin, Castilla-La Mancha (Spain)

The UGB spans about 16 000 km² of the south-eastern part of Spain's Central Plateau. Half of this is located within the province Ciudad Real, while three other provinces of the Castilla-La Mancha Autonomous Community (Cuenca, Toledo and Albacete) account for the rest.

The climate is semi-arid including low and irregular precipitation. The UGB is one of Spain's driest areas (Carmona et al. 2011). The hydro-geology in the UGB is naturally characterized by a close connection between surface and groundwater bodies, resulting in a series of lagoons and wetlands of unique ecological value. Covering an area of 5 500 km², the *acuífero Sistema 23* or *acuífero de La Mancha Occidental* is central to the UGB, not only from a hydro-geological point of view but also in terms of socio-economic activities. Agriculture maintains a strong presence in the area, where groundwater exploitation helped transform a largely poor rural region into an agricultural center. Since the 1970s major problems have arisen as a result of uncontrolled groundwater development, with irrigation accounting for 90-95 % of total water consumption (Carmona et al. 2010) and an increase in the irrigated surface area from 30 000 to over 200 000 ha in that period (GHC 2006). An average decrease of the water table of 30 m in piezometric levels in the years 1980 to 1992 has detached the aquifer from surface water bodies in many areas, resulting in the degradation of the wetlands of UNESCO's Mancha Humeda Biosphere Reserve and the RAMSAR-listed Las Tablas de Daimiel National Park (Carmona et al. 2010). These wetlands, which under semi-natural conditions would cover a total expanse of about 25 000 ha, today cover only 7 000 ha and, in addition, some of the rivers that were fed by aquifers have fall dry (Llamas and Custodio 2003a). This situation essentially induces social conflicts and controversial debates centered on the issue of water for development and water for the environment. In 1985, the Spanish government declared groundwater to be part of the public domain and granted river basin agencies power over aquifer management (Ross and Martinez-Santos 2009). Since the late 1980s, the Guadiana River Basin Authority has attempted to establish control and protection mechanisms for groundwater use (e.g., stopping the illegal development of wells, sale of water rights, development of sustainable crop-patterns). The 1985 National Water Act incorporates modern concepts such as environmental protection and the sustainable use of the entire water resource (Hernández-Mora et al. 2003). The overall goal of water management in the UGB is sustainable development focused on the recovery of aquatic ecosystems without inducing negative social and economic effects, related essentially to agricultural development. More recently the governance regime in the UGB has been characterized by an enduring lack of integration and mismatching agricultural and water policies. In recent years agriculture and water policies (EU, national and regional institutions), have merged into common objectives regarding natural resource conservation and towards sustainable agriculture practices (Varela-Ortega et al. 2011).

5.3 Spree, Brandenburg (Germany)

The Spree is a sub-basin of the River Elbe and flows through the federal states Saxony, Brandenburg and Berlin. The focus in this study was placed on the lower catchment of the river, which runs through Brandenburg and includes the Spreewald UNESCO Biosphere Reserve. This wetland splits into several branches that meander through a floodplain covering an area of 750 km², located 70 km south-east of Berlin, in the Lausitz region of Germany.

The area is characterized by low natural water availability, resulting from a mean annual precipitation of 530 mm and a potential evapotranspiration rate of 610 mm (Lahmer 2003). Climate change is expected to further reduce the natural water yield in the Spree Basin due to warmer summer temperatures, decreasing summer precipitation and extreme weather events, all of which will result in a decrease in groundwater replenishment of up to 42 % and a decrease in outflow of up to 24 %. The traditional regulated irrigation system of the Spreewald consists of ditches and weirs, which are used for the distribution and controlling of groundwater levels in the wetland areas (Dietrich et al. 2007).

The landscape-water regime of the Spree Basin provides a wide range of GESs for human well-being. During the last century the floodplain was diked and drained in order to intensify agriculture schemes. The landscape and soil formation of this area are the result of several glaciations during past ice ages. The area is characterized by sandy and poor soils (Büchner and Franzke 2009).

The main sectors depending on water resources and intact ecosystems are mining, tourism, agriculture, forestry and fisheries. Opencast lignite mining activities in the Lausitz area (one of the largest open mining areas in Europe), located close to the Spreewald Biosphere Reserve, constitute major threats to both water quantity and quality, and have negative impacts on GESs. Over the second half of the twentieth century dewatering for mining activities has resulted in an 8 km³ deficit in the groundwater balance in the Lausitz area, impacting upon the water supply to local municipalities and the environmental flows. Since the unification of the two German states in 1990, lignite mining has been substantially reduced and water is abstracted from the River Spree to refill aquifers and empty lignite pits (Pusch and Hoffmann 2000). Such large-scale disturbances to the natural hydro-geological settings impacted severely upon the ecological integrity of the running waters draining mining areas, both during operation and after abandonment of the pits.

After German unification natural resource management underwent abrupt changes in the political and socio-economic arena, often raising a variety of complex problems including altered resource use patterns, new constellations of land users and land owners, modifications of the water price, and nature conservation became much more prominent (Dosch and Schleyer 2005).

6. Results and discussion

The results obtained in the study initiated in an attempt to answer the research questions outlined in **table 1** are organized as follows: in **chapter 6.1** the degree of vertical and horizontal integration according to the criteria and indicators captured in **table 4** are investigated, and subsequently in **chapter 6.2** the drivers of institutional responses to groundwater ecosystem management in each case study are described and the manner in which institutions operate to integrate social and ecological perspectives on GESs and to produce effective action are characterized.

6.1 Research topic 2: Analysis of vertical and horizontal integration

Upon completion of data collection, the case study databases were analyzed systematically. The results of vertical and horizontal integration are demonstrated in the following two sections.
Whereas vertical integration is determined by multi-level interactions of governance and management activities, horizontal integration was analyzed on the basis of different AAs represented by actors and ASs. Finally, the degree of vertical and horizontal integration influencing the management of GESs across the case studies was determined. The outcomes of ASs were used to describe these impacts, including different institutional settings and measurable effects. This part of the results demonstrates how integration changes over time across the case studies.

6.1.1 Vertical integration

To explain vertical integration, first absolute numbers of all of the ASs and actors participating in groundwater management in the respective case studies are outlined in **table 6**. Second, a correlation matrix between ASs and actors describes multi-level interactions (**table 7**).
The results of the analysis show that the degree of vertical integration differs in all three case studies and is highly influenced by the diverse circumstances of the individual case.

Table 6 Overview of the number of action situations and actors, and the number per corresponding administrative level in each case study

	Sandveld	UGB	Spree
Analytical time horizon	1988 - present	1985 - present	1990 - present
Number of ASs	17	14	11
Number of ASs per administrative level			
▪ international	-	-	-
▪ national	2	5	3
▪ regional	3	-	2
▪ basin	3	-	1
▪ sub-basin	9	10	6
Number of state actors	11	10	15
Number of non-state actors	20	19	18
Number of actors per administrative level			
▪ international	4	1	3
▪ national	11	12	8
▪ regional	8	5	18
▪ basin	2	2	-
▪ sub-basin	6	9	4

In each case, the sub-basin level constitutes the central level at which most ASs take place. There are certain responsibilities and tasks distributed between the different levels. In general, the content of ASs at lower levels ranges from stakeholder meetings, including the discussion and development of projects, to the implementation of concrete plans and measures. However, formulating strategic management goals and policies occurs during ASs at higher levels. It is vital that the knowledge and perspectives of actors at all levels be considered during these policy phases. The strategic goals are formally binding for all actors, and are established to determine a desirable state of the entire water system, including both socio-economic and environmental goals and values.

Most actors in the Sandveld and UGB represent the national level whereas the majority of actors in the Spree Basin represent the regional level. Actors from the basin level are poorly represented. It is important to note that the central actor in the UGB is the Guadiana River Basin Authority (RBA), which represents the basin level and is active during all ASs. Actors from sub-basin level are more prominent and include individuals (e.g., farmers), irrigation boards and conservation associations.

The number of non-state actors involved in groundwater management is high in the Sandveld and UGB whereas in the Spree Basin the divide between state and non-state actors is almost even.

Table 7 provides further information about the actors from different levels involved in groundwater management processes (ASs) at different levels. This general overview of the multi-level interaction demonstrates the distribution and linkages between actors and ASs. The size of the cross highlights the intensity of the actors' involvement in groundwater management: **X**: high; **x**: moderate; x: low. The intensity is calculated on the basis of the number of actors from a certain level (e.g., regional level) active at a certain level on which an AS took place (e.g., international level). These results are deduced from the queries.

Table 7 Multi-level interactions across case studies

Level of AS	Actor level														
	International			**National**			**Regional**			**Basin**			**Sub-basin**		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
National	x	x	x	x	**x**	**x**		**x**	**x**		x				x
Regional	x		x	**x**		x	**x**		**X**						**x**
Basin	x		x	x		x	**x**		**x**	x					
Sub-basin	x	x		**x**	**x**	x	**X**	**X**	**X**		**x**		**x**	x	**X**
A: Sandveld; B: UGB; C: Spree Basin															

It becomes evident that actors from the national and regional level exhibit the highest involvement at all levels – especially at sub-basin level. Actors from lower levels (basin and sub-basin) are hardly involved in ASs at higher levels and, consequently, local perspectives and knowledge of GESs are not communicated during ASs at higher levels.

Sandveld: The intensity of national and regional actors' involvement is higher than that of international, basin and sub-basin actors. With the exception of actors from the basin level, all actors are active on levels other than just their own level. It is important to note that actors from higher levels are involved in ASs at lower levels, whereas none of the actors operate in ASs occurring at levels higher than their own.

Actors from the international level are active at four levels. They constitute non-state actors and support funding for different programs and projects. As they have no active role in groundwater management in South Africa, the intensity of their involvement at all four levels is low. National actors, the central national actor being the Department of Water Affairs (DWA), are involved in ASs at four levels, the intensity of which is moderate at regional and sub-basin level and low at national and basin level. Regional actors are highly active at sub-basin level and moderately involved at basin and regional level. The central actors are the regional DWA, the Department of Agriculture, the Department of Environmental Affairs and CapeNature (non-state actor). Actors from the sub-basin level exhibit moderate involvement at their own level (essentially farmers).

UGB: Actors from the national and regional level exhibit a higher intensity of involvement in ASs at national and sub-basin level than actors from the international, basin and sub-basin level. Actors from higher levels are involved in ASs at lower levels and actors from lower levels are involved in ASs at higher levels (except sub-basin actors as they are solely involved at their own level).

International actors, mainly the European Union (EU), are part of ASs at national and sub-basin level with a low intensity of involvement as they are not actively involved in groundwater management. National actors, both state and non-state, are moderately active at both national and sub-basin level. Actors representing the regional level are highly involved at sub-basin level. Actors from the basin level exhibit a moderate degree of involvement at sub-basin level and low involvement at national level. Sub-basin actors solely operate at their own level, with a low degree of intensity. These include farmers, irrigation associations and conservation groups.

Spree basin: Regional actors play the most prominent role in groundwater management, the majority of which are state actors such as the administration of the biosphere reserve, the State Office of Environment, Health and Consumer Protection, and the State Office of Mining, Geology and Resources. In contrast to the previous two study sites, actors from higher levels are active in ASs at lower levels and actors from lower levels are active in ASs at higher levels.
International actors are active at national, regional and basin level, with a low intensity of involvement. National actors are moderately active at their own level, with a lower level of involvement at regional, basin and sub-basin level. Actors from the regional level are moderately active at national and basin level and highly active at regional and sub-basin level. Actors at the sub-basin level are active in ASs at their own level as well as at regional and national level.

6.1.2 Horizontal integration

Having elaborated on vertical integration, in the following the degree of horizontal integration is presented. In **figure 7** all of the AAs that play a role in groundwater ecosystem management, represented by ASs and actors (it is possible to link more than one AA to an ASs or actor), are summarized. As agriculture is the dominant sector in the UGB, and the most important for societal development and economic growth, it is not surprising that most ASs and actors represent this AA. The results revealed that not only the dominant sectors but also other sectors are consulted during and integrated in groundwater management.

The central AAs are agriculture, water ecosystem management, nature protection, water supply and spatial planning. The degree of intensity varies in the three case studies and is explained in the following.

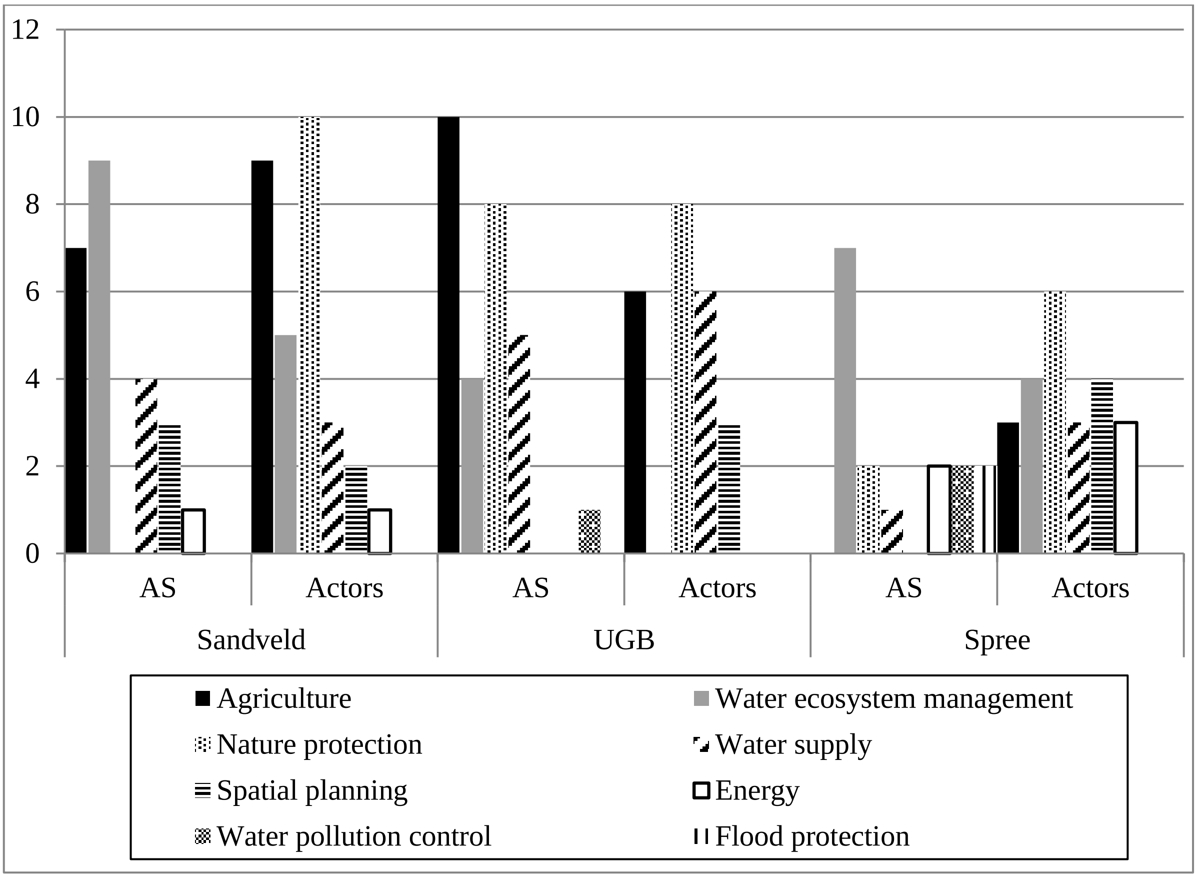


Figure 7 Overview of the action arenas pertaining to groundwater

Sandveld: Two AAs of central importance were identified, namely agriculture (ascribed to 7 ASs) and water ecosystem management (ascribed to 9 ASs). In addition to the general allocation of groundwater for irrigation purposes, the first includes the tools, measures and technical infrastructures required to govern water in the agriculture sector. Water ecosystem management alternatively refers to holistic and comprehensive management approaches for landscape-water systems (see **appendix E**, A AS9-11). The AA spatial planning is considered to be a connecting sector in the Sandveld as it operates mostly on behalf of other sectors. This AA is responsible for the creation of spatial plans and technical and hydro-geological reports for local, regional, national and international clients.

The highest intensity of AAs engaged in by actors relates to agriculture and nature protection as they operate during almost all ASs. The main distinction between water ecosystem management and nature protection stems from the fact that the latter occurs on a smaller scale (e.g., protection of wetlands) than water ecosystem management. Water supply and energy play a minor role in groundwater management in the Sandveld.

UGB: Groundwater management in the UGB is shaped by five different AAs involved in ASs. The majority of AAs is constituted by agriculture followed by nature protection, water supply and water ecosystem management. The majority of actors represent the sector nature protection (non-state actors such as Ojos del Guadiana Vivos, WWF, Spanish Society of Ornithology) although groundwater management is central to the AA agriculture (both state and non-state actors). The results indicated that in most instances actors from the environmental sector are little involved during planning and decision-making. Usually they are consulted or informed at a very late stage in the management process, if at all, which triggers conflicts and prompts opposition to official decisions (e.g., drafting of the management plan for the UGB; see **appendix E**, B AS 9-14). Actors representing the AA water supply are mainly state actors from higher levels.

Spree Basin: The Spree case study revealed the highest number of AAs involved in groundwater management (ascribed to 7 ASs). Unlike in the two other case studies, it was not possible to identify a central AA (such as agriculture). The distribution between the AAs was more or less even. Nevertheless, in the Spree case study groundwater management was found to be of fundamental concern in the contexts of environmental management and nature conservation as six actors represented the AA nature protection (both state and non-state actors) and seven ASs were linked to water ecosystem management. The AA energy was important in the Spree as lignite mining is one of the main industrial sectors impacting upon water management. The Spree was the only one of the three case studies incorporating the AA flood protection as the area experiences regular flood events.

6.1.3 Case study comparison: vertical and horizontal integration

Substantial differences in the levels of vertical and horizontal integration during the management of groundwater and the impacts on GESs were revealed (**table 8**, based on **appendix F**). The comparison and the following discussion are embedded in the broader national context of the respective case study sites.

Table 8 Cross comparison of vertical and horizontal integration across the case studies

	Sandveld	UGB	Spree
Vertical integration			
Groundwater management is shaped at different levels	partly	no	yes
Actors operate at different levels of management processes	partly	partly	yes
Non-state actors are involved in management and set up rules that directly affect them	partly	no	partly
Horizontal integration			
Actors from different sectors are involved in decision making	yes	partly	yes

A review of the key findings in relation to vertical and horizontal integration regarding the indicators highlighted in **table 4** is presented in **table 8**. It is important to note that the indicators referring to vertical and horizontal integration reflect management processes over time rather than describing a specific action during a certain period.

Many economic practices, and the governing institutions, were geared towards altering the pattern of the landscape water regime in order to achieve optimal circumstances for agriculture or mining activities. In so doing, they changed underlying ecological processes and reduced the availability of many GESs. Over the last two decades, ecological thinking and an awareness of ecosystem functions and processes as underlying conditions supporting human well-being have grown continuously. In this context, periods of change were identified across the case studies, shaped by different degrees of integration. It was not possible to determine a clear relationship between different degrees of vertical and horizontal integration and the overall state of GESs (e.g., improvement of water quality). However, the results indicated that all groundwater regimes show some tendency towards adaptive management approaches, which in turn positively influence the management of GESs. This statement is reinforced by evidence derived from case study insights presented below.

Water management in the Sandveld is dominated by a top-down regime featuring huge disparities in cooperation between the administrative levels. At the same time, South Africa possesses ground breaking institutional frameworks such as the National Water Act, which aims to bring about the requirements for equity, sustainability and the efficient use of all water resources (Ashton et al. 2006). Unfortunately, the groundwater regime of the Sandveld does not provide for effective and sustainable resource regulation and allocation. As groundwater policies are basically developed at the national level – in contrast to Germany and Spain where groundwater management is shaped at lower levels – there exists hardly any discourse or exchange of experience and knowledge with actors from lower levels. Participation at lower levels only occurs during informal programs and projects but is not implemented in the formal procedures at higher levels.

Furthermore, the Sandveld's water sector lacks horizontal integration. Water management at national level is highly fragmented, without any consensus between the different sectors. However, the Sandveld has made some progress towards sectoral integration between the agriculture and conservation sectors, and bottom-up approaches include a wide array of stakeholders (see **appendix E**, A AS13-17). This led to an improvement in the quality of plans and projects, and stakeholders (e.g., farmers) support the implementation of new approaches (e.g., biodiversity guidelines for potato production). Similar bottom-up approaches were observed in the Spree, where community engagement initiated conservation programs to maintain and protect different GESs.

Conservation programs (in the context of groundwater management) in South Africa in general, and in the Sandveld in particular, are relatively young. Government accountability for decisions concerning ecosystem services is weak and in the case of specific GESs there is frequently no accountability whatsoever. However, management activities in the Sandveld indicate positive impacts, in line with GESs aspiration and objectives. In addition to provisioning services (e.g., increased efficiency of water use), positive impacts on regulating services (e.g., flora/fauna habitat) and cultural services (e.g., development of hiking trails through the Sandveld) were also identified. In spite of these positive impacts on GESs, the prescribed hydro-geological protection measures are threatened by a lack of human and financial resources and the absence of strong groundwater leadership at both higher and lower levels.

Spain's water management is shaped by a hierarchical system with hardly any multi-level or sectoral integration. In most regions of Spain the water sector is strongly influenced by the agriculture sector, as water use for irrigation plays a major socio-economic role for thousands of rural livelihoods. The Guadiana RBA is the leading actor in the UGB and is responsible for groundwater management. However, enforcement is weak and the ecological dimension of groundwater has played only a minor role in recent decades. Although participation exists at the institutional level, implementation is insufficient in the UGB, where participation barely takes place. The representation of environmental groups and other sectors at higher levels is barely significant and the integration of different perspectives and knowledge of GESs is low. Like Germany, Spain has to fulfill the mandate of the EU Water Framework Directive (WFD), which encourages the active involvement in water management of all interested parties from different levels. While the German case study provided positive examples of public participation influencing the outcome of plans and working processes, the Spanish case study site was slower in making progress.

Furthermore, the groundwater governance regime of the UGB is characterized by enduring social conflicts and mistrust between users and official state bodies. Over the last two decades, different policy approaches have been implemented in an attempt to solve the serious situation in the UGB, addressing both social conflicts and ecological degradation (see **appendix E**, B AS3-8). Bans, controls over water use (e.g., pumping restrictions) and compensatory payments were put in place to encourage farmers to cut down on water abstraction. These were unsuccessful as they failed to mitigate conflicts and balance GES trade-offs. On the contrary, the illegal development of wells and water abstraction increased due to a lack of control by the RBA. The past and current groundwater governance regimes of the UGB are deemed to be very inefficient in terms of implementing measures and monitoring and control of water abstraction. The social conflicts and the enduring lack of integration and the mismatching of various agricultural and water policies are as challenging for the UGB as the continuous degradation of GESs.

Germany's water management includes three primary levels of competence: the federal government, the federal states and the municipalities. There is no strict hierarchy between the levels but each has its own specific responsibilities. Abrupt changes to Germany's political and economic structures during the early 1990s raised a variety of complex problems in the field of groundwater management. Similar to South Africa, where the political regime shift opened a window for institutional water reforms, the previous top-down water management practiced in East Germany started to change during the early 1990s, including an increase in vertical and horizontal integration. To date, the centralized management regime has addressed only a small number of provisioning GESs important for agriculture and mining industries and ignored regulating, supporting and cultural services. During the last decade, various bottom-up processes in the Spree Basin, including multi-level and sectoral integration considering a wide array of GESs, took place (see **appendix E**, C AS4-6). Since the 2000s, participation has been increasingly promoted although many management processes are still dominated by state-actors from the regional level. Participatory approaches in the Spree Basin range from simple forms of stakeholder involvement (e.g., public hearings, opportunities to comment on plans) to the establishment of temporary or permanent actor networks.
The study revealed relationships between an improvement of vertical and horizontal integration (e.g., multi-level interactions), management outcomes (e.g., development and acceptance of new institutions), implementation (e.g., conservation measures) and the improvement of various GESs (e.g., base flow, flora and fauna habitat).

Vertical integration increased in the Sandveld and Spree Basin case studies, whereas the UGB case study performed poorest in terms of integration structures. The UGB revealed hardly any improvements in terms of integration structures towards adaptive and integrated groundwater management. This can be related to the enduring social conflicts in the UGB. By contrast, horizontal cooperation structures increased in all three case studies. It is important to note that this shift is often very difficult to achieve, as dominant sectors using the bulk of groundwater for industrial purposes (here agriculture and mining) are often unwilling to cooperate with other sectors that depend either directly or indirectly on GESs.

6.2 Research topic 3: Institutional response

In this chapter the drivers of institutional responses to groundwater ecosystem management in each case study are described, before the manner in which institutions operate to integrate social and ecological perspectives on GESs and to produce effective action are characterized. Integrative perspectives were defined as those that address GESs and human well-being simultaneously, while the effectiveness of institutions was analyzed based upon a set of variables incorporating the degree of implementation (fully, partly or hardly) and their corresponding effects on GESs. The degree of implementation was analyzed based upon documentary reviews and expert knowledge.

Institutional responses within the individual case studies were triggered by a diverse set of drivers of change (**table 9**).

Table 9 Types of drivers of change and their occurrence across the case studies

Driver type	Sandveld	UGB	Spree
Ecological	3	4	2
Legislative requirements	1	4	2
Economic	1	1	2
Political regime shift	1	-	1
Social	1	1	-
Cultural	-	-	1
Technological development	1	-	-

In the Sandveld and the UGB the majority of responses were induced by ecological drivers and international or national legislative requirements; the Spree Basin provided a relatively even distribution of drivers of change. The consequences of these drivers in producing effective and integrated institutions varied much more than the drivers themselves (**table 10**). Presented in **table 10** is an aggregated view of formal and informal institutions as the focus is on environmental and societal effects. The comparative analysis of the case study results indicated that informal institutions are not commonly used in groundwater ecosystem management. Detailed information on the role of

institutions, including their regulatory provisions and measures, the degree of implementation as well as their effectiveness in relation to GESs, is provided in **appendix G**.
Below the manner in which drivers of institutional response prompted institutional change over time is outlined in more detail for each case study.

Table 10 Aggregated overview of the effectiveness and integrative perspectives of institutions

	Effectiveness of institutions	Integrative perspectives	Environmental effects	Societal effects
Sandveld	Medium	High	• Expansion of protected areas • Water savings • Sustainable farming practic-es	• Water user association • Industry engagement • Education/growing awareness • Public participation
Upper Guadiana Basin	Low	Medium	• Little water savings • Reforestation	• Groundwater user associations • Compensation pay-ments • Lack of cooperation and communication • Illegal water abstrac-tion
Spree	High	High	• Water protection zones • Expansion of protected areas • Improvement of the overall water balance	• Water pricing system • Education/growing awareness • Public participation • Compensation pay-ments, purchase of land

The aggregated overview is a simplified representation of the most important environmental and societal effects in the respective case study **(**based on **table 18** in **appendix G**).

6.2.1 Analyzing institutional response in the case studies

Sandveld

The Sandveld case was dominated by ecological drivers of change (**table 9**) triggered by the over-abstraction of groundwater for irrigation purposes and the enduring clearing of natural vegetation for potato and rooibos tea production. With the end of the Apartheid era, South Africa's water legislation underwent significant institutional changes, including a shift in social and ecological perspectives on groundwater. Institutional response took place at different levels of management action: national, regional, basin and sub-basin level. This situation induced massive changes with respect to administrative responsibilities and innovative regulatory instruments for water assessment, planning and management, economic instruments to influence water use patterns, as well as cooperative measurements to enhance participation (**appendix E**). Together, economic and ecological drivers triggered a basic rethinking of what groundwater use and protection means. A major attempt was made by the potato industry, the conservation sector, farmers and local municipalities to integrate and mainstream ecological thinking in the production sector (**appendix E**, A AS9-15). An outcome of institutional response, both formal regulatory mechanisms and informal guidelines for the Sandveld farmers take into account provisioning, regulating and cultural ecosystem services. Lately, non-compliance with national legislative requirements (National Environmental Management Act of 1998) has hampered the implementation of farming practices favoring biodiversity, which are not legally recognized. As a response to this dilemma, a task team comprising state and non-state actors was developed and scheduled a law enforcement strategy (**appendix E**, A AS16).

The effectiveness of institutions is rated medium in the Sandveld, and the integrative perspectives on GESs high (**table 10**). Most important institutions managing groundwater in an integrative manner include a diverse set of regulatory provisions and measures (see **appendix G**). It became evident that formal institutions established at national level (National Water Act, National Groundwater Strategy) hardly provide any measurable effects, whereas informal institutions constituted at lower levels indicate positive impacts on the management of GESs. The effectiveness of institutions is sub-divided into environmental and societal effects. The latter incorporate the establishment of a local water user association and a substantial increase in industrial engagement in natural resource management, such as the establishment of the Greater Cederberg Biodiversity Corridor and the development of biodiversity best practices for potato production. Environmental effects, including the expansion of protected areas and the application of sustainable farming practices, were identified. These farming practices favoring biodiversity could be more effective if the issue of non-compliance were to be solved in the near future.

UGB

The UGB case is dominated by ecological drivers of change and a set of legislative requirements (**table 9**). The former was identified as being the general driving force as the ecological consequences of intensive groundwater use for irrigation over the last 40 years have prompted a great amplitude of institutional response. This response includes international and national agriculture and water reforms to solve the unsustainable use of groundwater and the enduring degradation of ecosystem services. Many of these responses were, to a great extent, determined by strict quota

systems or bans on the drilling of new wells, while others included compensation payments for farmers and various technical solutions such as water transfer schemes in which only a relatively small number of GESs was addressed (see **appendix E**, B AS1-6).
The WFD represents a milestone in EU water management. Spain, like all of the other member states, adopted the WFD to ensure the good ecological status of all water bodies by the year 2015, including a broad mandate of innovative institutional responses to incorporate economic and ecological considerations: water pricing, ecological objectives, political processes, public participation and new approaches to water planning (see **appendix E**, B AS7). The WFD and Spain's National Hydrological Plan triggered the development of the SPUGB. The drafting of the plan took more than eight years and was initially opposed by the majority of actors in the UGB, as the content of the plan focused primarily on the water requirements of large commercial farmers rather than considering the protection of aquifers and wetlands (Knüppe and Pahl-Wostl 2011). Today, the special plan is considered a groundbreaking institutional response facilitating large-scale efforts to restore the complete SES of the UGB (see **appendix E**, B AS8-13).

The effectiveness of institutions in the UGB is rated low, while integrative perspectives on GESs are medium (**table 10**). The central institutions managing GESs are exclusively formal regulatory provisions and measures such as the Spanish Water Act, the EU Agro-Environmental Program, EU WFD, EU Groundwater Directive, and the National Hydrological Plan (**appendix G**). The majority of these institutions is hardly implemented in the Upper Guadiana Basin and, therefore, has barely any positive environmental or societal effects on groundwater management. The few benefits that have been produced include the establishment of groundwater user associations and payments for compensation measures. Even though the institutional responses have led to some short-term ecological improvements (see **appendix E**, B AS2-7), the overall challenges remain the same. Additionally, certain institutions and the lack of effective implementation have amplified some negative societal effects, including the illegal expansion of water abstraction and deepening the enduring social conflicts between groundwater users and managers.
Both the EU WFD and Groundwater Directive focus to a large extent on water quantity standards and less on groundwater dependent ecosystems and the services they provide. While implementation of the WFD has started in the UGB, the Groundwater Directive is hardly implemented. The general problem of institutional implementation in the UGB can be associated with a lack of vertical and horizontal integration and the enduring social conflicts (see **chapter 6.1**).
Essentially, the only two environmental effects were water savings and the reforestation of land associated with the implementation of the SPUGB.

Spree Basin

The Spree Basin case was not dominated by specific drivers of change (**table 9**). In addition to ecological and economic drivers, the existing legislative requirements were another important driver of change impacting groundwater management in the Spree. The unification of Germany and corresponding economic drivers had enormous impacts on the institutional responses, such as the liberalization of water markets and international standards for water quality and quantity (see **appendix E**, C AS1-2). At the same time, ecological conditions were recognized as being a high priority area requiring improvement. In response, the Federal Republic of Germany designated areas of great importance for nature conservation, such as the Spreewald UNESCO Biosphere Reserve in 1990. Ecological and cultural drivers of change triggered different responses for the protection of the ecological and the cultural heritage of the Spreewald. This resulted in the establishment of the Spreewald Riparian Land Project. This large-scale conservation project funded by the German Federal State was initiated and carried out by local agencies and stakeholders seeking to safeguard the hydrological flows and to maintain the flora and fauna of the wetlands of the Spreewald (see **appendix E**, C AS4-7). The institutional response incorporated compensation payments, land purchasing, environmental management plans, and conservation measures to protect different types of GESs among other things. Like Spain, Germany adopted the WFD. Institutional responses linked to this international legislative requirement can be seen in the implementation of measures developed as part of the Spreewald Riparian Land Project to ensure the good ecological status of all water bodies by the year 2015.

As the mining sector, located along the upper reaches of the River Spree, is responsible for hydrogeological modifications, the institutional response is triggered mainly by international and national legislative requirements (e.g., environmental assessment analysis and development of compensation measures). The mining sector is greatly influenced by economic drivers. However, the most important GES taking into account is associated with power-plants.

The effectiveness of institutions and integrative perspectives on GESs are rated high in the Spree (**table 10**). Important institutions for the management of groundwater incorporate regulatory provisions and measures developed at international, national and local levels, and set incentives for stakeholders to support and accept innovative approaches to protect GESs. The Brandenburg Federal Water Act and the Federal Nature Conservation Act are fully implemented, whereas the EU WFD and the Groundwater Directive have hardly any environmental effect (**appendix G**). At sub-basin level, the Spreewald Riparian Land Project integrated social and ecological perspectives on groundwater ecosystem management and, in addition to participation processes and a raising of awareness of ecosystem services, included concrete measures such as water pricing systems and compensation payments. The environmental effects included the establishment of water protection zones, the expansion of protected areas and a general improvement of the landscape water system along certain parts of the River Spree. An improvement of both water quality and quantity can be observed along some parts of the River Spree and in the Spreewald.

6.2.2 Lessons learnt from the management of groundwater ecosystem services across the case studies

According to Ostrom and Cox (2010), the investigation of different institutions around the world has achieved great progress, which had been necessary to move forward from the over-reliance on universal remedies to improve the state of GESs including various dynamic processes and functions supporting human well-being.
The results indicated a growing recognition for each of the groundwater regimes across the three case studies of the importance of steering societies towards sustainable management in order to maintain GESs for present and future generations. The case studies differed in terms of the responsible authorities, institutions and legal requirements for groundwater regulation and protection. As the results demonstrated, well-crafted regulatory frameworks are not effective if they are not implemented in practice (e.g., EU Groundwater Directive, South Africa's National Water Act). This in turn has substantial consequences for GES trade-offs.

Summarized in **table 11** are 11 GESs that play an important role across the three cases. Supporting services are not included as they are necessary for the production of all other ecosystem services.

Table 11 Groundwater ecosystem services in the three case studies

Groundwater ecosystem services	Sandveld	UGB	Spree
Irrigation	X	X	-
Domestic supply	X	X	X
Power plants	-	-	X
Purification/waste treatment	-	-	X
Drought buffer	X	X	X
Erosion/flood control	-	-	X
Base flow	X	X	X
Flora/fauna habitat	X	X	X
Recreation and tourism	X	X	X
Aesthetic beauty	X	X	X
Education and research	X	X	X

The findings presented in **table 11** demonstrate that across the case studies different GESs are used, enjoyed or consumed by humans simultaneously. This in turn results in some GESs being traded-off at the expense of others.

The lessons learnt from the cases reveal that institutional response is primarily embedded in long-term management processes in which surprises or crises stimulate reorganization, and can produce renewable and innovative opportunities for new ways of managing natural resources in order to avoid trade-offs.

All of the case studies illustrated that institutional response is caused by multiple, interacting drivers of change, and that the effectiveness of implementation depends on the different circumstances of the overall SES. Political and economic shifts as well as legislative requirements open windows of opportunity, which allow for new approaches to natural resource management at different levels on the one hand and create a variety of complex challenges including altered resource use patterns, new constellations of land users and land owners, and modifications of the water price on the other hand. Ecological drivers are dominant in all three case studies, which triggered a basic rethinking of the role of GESs in formal and informal institutions. Especially in the case studies characterized by intensive agriculture, the significance of protecting GESs increased. Social and cultural drivers and technical development played a minor role in generating institutional response in the three case studies.

It became evident that the effectiveness of institutions focusing on a single instrument is rarely adequate to implement an integrative response. It was observed that most institutions generally incorporate multiple regulatory provisions and measures to support their effective implementation.

The results indicated that there are often no clear links between ecological drivers and the institutional response when addressing environmental challenges. This disconnect became particularly evident in the UGB, where the majority of institutional responses was triggered by ecological drivers but their effectiveness was low and the ecological state of GESs remained poor. Furthermore, it was observed that legislative requirements often have a stronger impact in terms of pushing institutions towards integrative perspectives than other drivers. Although the institutional response to the solving of environmental challenges grew continuously, the effectiveness and implementation of institutions often require longer timeframes before an impact can be made and a broad constituency of support can be established. Furthermore, the main trade-offs between provisioning services (irrigation, domestic supply and power plants) and between regulating and cultural services still exist.

Lessons learnt from the management of GESs across the case studies are summarized below.

Provisioning services: As provisioning services play a crucial role in supporting human well-being and economic development, institutions attach great importance to them. These GESs (e.g., irrigation, mining activities, drinking and sanitation water supply) are regulated by stricter institutions

and mechanisms (basically formal laws) controlling their use and allocation (registration and licensing of water abstraction, pricing systems) than those for regulating and cultural services. The previously rather narrow perspective of provisioning services has shifted over the last two decades towards integrative perspectives on multiple ecosystem services. Institutional response aims to solve the trade-off dilemma between provisioning (direct) ecosystem services and all other ecosystem services, which is reflected in diverse ecological problems and social conflicts across the cases.
Lessons learnt. The Sandveld and the Upper Guadiana Basin demonstrated how institutional responses incorporate both the water requirements for irrigation purposes and to maintain environmental flows and ecosystem services (e.g., biodiversity best practices for potato production in the Sandveld, Special Plan for the Upper Guadiana Basin). At both case study locations instruments had been developed to mainstream the protection of GESs in the agriculture sector. It is important to note that the effectiveness varied between the two cases, however.

Regulating services: To a certain extent, it was possible to discern the recovery of certain regulating services in the context of institutional response. In general, regulating services often remain unrecognized and actors are unaware of them until a certain service declines or is traded-off with a corresponding impact on human well-being. For example, the intensive abstraction of groundwater for agriculture or mining activities negatively influences the groundwater base flow to rivers and wetlands, which in turn supports groundwater specific flora and fauna habitats. The UGB demonstrated a typical example of this concern, where intensive irrigation was traded-off at the expense of most regulating and cultural GESs. It proved essential to include local communities and stakeholders by developing and implementing new institutions to protect regulating services.
Lessons learnt. Bottom-up responses in the Sandveld incorporated multi-stakeholder processes during the development of the Greater Cederberg Biodiversity Corridor and the establishment of biodiversity best practices for potato production. The result was a high level of acceptance of new approaches to protect regulating services without negatively impacting upon provisioning services and, consequently, the livelihoods of people in the Sandveld. The Spreewald Riparian Land Project represented a groundbreaking institutional response, acknowledging different regulating GESs (**table 11**). Within a multi-stakeholder process, a conservation and development plan was formulated, including different regulatory provisioning and measures supporting base flow and flora and fauna habitats among other things.

Cultural services: All three case study locations featured internationally protected ecosystems (Sandveld: Verlorenvlei RAMSAR Site; Upper Guadiana Basin: Las Tablas de Daimiel National Park RAMSAR Site; Spree: Spreewald UNESCO Biosphere Reserve) providing opportunities for recreation and tourism as well as education and research. Therefore, cultural services played a cru-

cial role across the case studies (**table 11**). Unfortunately, many cultural services were not adequately or explicitly captured in the institutional responses – especially in areas making intensive use of provisioning services. As groundwater is an essential component of everyday life, integrated throughout different cultural services in the case studies, institutional response slowly began to incorporate certain non-material benefits that people obtain from groundwater ecosystems.
Lessons learnt. The protection and maintenance of cultural services are acknowledged in formal institutions in South Africa (e.g., National Water Act, National Water Resource Strategy) and in informal institutions developed in the Sandveld (e.g., Greater Cederberg Biodiversity Corridor). The Spree acknowledges cultural services solely in informal institutions (e.g., Spreewald Riparian Land Project). Both cases demonstrated that the willingness of actors to support and maintain cultural services increased as their well-being depended to a large extent on these services.

In summary, the results and lessons learnt from the comparative case study analysis of the institutional responses of groundwater governance of ecosystems revealed general features across the case studies. First, institutional responses tend not to be integrated, and second, well-crafted institutions are not sufficient to produce socially, ecologically or economically satisfactory results. It was shown that governance tends to favor the management of provisioning ecosystem services over regulating and cultural services. While provisioning services may be more valuable than other services, it is suspected that the public good nature of regulating and cultural services leads to underinvestment in these. These results are broadly similar to many assessments of ecosystem services (MA 2005, Raudsepp-Hearne et al. 2010).

7. Conclusions and outlook

A fundamental challenge for water managers all over the world is to understand the dynamics of ecosystem services and human well-being, and to develop adaptive and sustainable management practices dealing with these complexities. To meet the steady and increasing demand for water they must reflect new social priorities, economic realities and environmental goals. The successful management of water resources and ecosystem services requires adaptive governance systems and a capacity to respond to change and uncertainty (Folke et al. 2005, Seward et al. 2006, Pahl-Wostl 2009). Transformation towards adaptive governance is a long and often challenging process that takes decades rather than years, and which cannot be brought about by strict top-down implementation but requires a process of learning and change (Pahl-Wostl et al. 2007).
Berkes and Folke (1998) suggested that research into social-ecological systems (SESs) acting as complex adaptive systems is urgently needed, including research into their powerful reciprocal feedbacks and linkages. Analytical frameworks exploring SESs, including groundwater ecosystem service (GES) linkages and trade-offs, and the overall governance and management regime dealing with this system complexity, are rare. The findings presented in this thesis help to fill this gap.

The study presented here represents a contribution to interdisciplinary research in the field of groundwater and ecosystem services. The research supported a comprehensive understanding and knowledge of complex groundwater regimes governing GESs. It bridged social and natural science as a precondition for present and future natural resource management to ensure livelihoods, economic growth and ecological integrity.

Presented in the thesis are the results of a comparative case study analysis, the aim of which was to investigate groundwater regimes nested in complex SESs. The overall goal behind the study was to achieve a deeper understanding of how GES linkages and trade-offs are structured and governed between natural and human water needs.
The research focus was on the governance of groundwater regimes and the sustainable management of GESs in three case study regions: Sandveld (South Africa), Upper Guadiana Basin (UGB) (Spain), and Spree Basin (Germany). Groundwater management within a time horizon of more than twenty years was investigated in each case study in order to ascertain relationships between governance and the management regime and the state of GESs by taking shifts over time into account. These shifts included both management performance and ecological conditions. The research was designed to investigate three main topics and a set of corresponding research questions captured in **box 3**.

Box 3 Research topics and questions

Research topic 1

The development of an analytical framework building upon the management and transition framework (MTF) to analyze complex governance regimes and GESs

Research question:

- What are the requirements of an analytical framework to support context-sensitive case study analysis of groundwater regimes governing GESs?

Research topic 2

Comparative case study analysis of vertical and horizontal integration and their impacts on the management of GESs towards adaptive and sustainable groundwater governance

Research questions:

- How does vertical and horizontal integration evolve in each case study?
- Does a higher degree of integration foster the sustainable management of GESs?

Research topic 3

Investigation of the role of both formal and informal institutions and their influence on GESs nested in complex SESs

Research questions:

- What are drivers of change and how do they influence institutional response in each case study?
- Does the institutional response incorporate integrative perspectives on GESs towards effective groundwater ecosystem management?

The three research topics were addressed in succession as they were each based upon one another.

One of the main objectives of this study was the development and application of a novel framework to enable a context-sensitive analysis without being restrictive to case specifics. The framework served as a diagnostic approach rather than as a means to obtain simplistic answers to system complexity. A corresponding database approach supported the in-depth analysis of groundwater regimes and helped provide insights into how management behavior impacts upon GESs. In the following, the three research topics will be critically evaluated and the findings summed up.

Research topic 1 constituted a good entry point for the examination of the empirical cases. The total system database (TSD) was applied to answer the questions related to research topic 2, in which several specific action situations, actors and outcomes were identified. Linkages, feedbacks

and impacts between groundwater regimes and GESs were investigated on the basis of vertical and horizontal integration structures crucial for adaptive management. Under research topic 3 the TSD was applied to investigate drivers of institutional responses to groundwater ecosystem management in each case study, and to characterize how institutions operate to integrate social and ecological perspectives as well as produce effective action.
The key findings of the three case studies according to research topic 1, 2 and 3 are summarized in **table 12**.

7.1 Summary of the key findings

The determination of the relationships between different degrees of vertical and horizontal integration and the management of GESs across the case studies posed great challenges. The first related to the literature review and expert interviews as the term GES and the ecosystem services approach are not widespread in the political and institutional arena of groundwater management. Second, alterations in groundwater governance and management regimes (e.g., breaking with traditional structures and the abandoning of long held habits) are difficult to detect. Third, the recovery of groundwater-dependent ecosystems and associated services (e.g., improvement of water quality) encompass a long-term horizon for the measurement of effects that goes beyond the scope of this research. Institutions play an important role in governing GESs addressing both short and long term sustainability. It is crucial that institutions provide the capacity for integrative perspectives by considering both the social and the ecological dimension of groundwater in order to support social well-being, economic development and ecological integrity.

Table 12 Summary of the key statements and findings of the research topics

Research topic	**Key statements and findings**	**Found in…**
1	The overall requirements of the novel framework can be summarized as follows: → open to different scientific concepts and world views, → include and address different types of local knowledge and stakeholder perspectives, → capable of handling different types of data (quantitative and qualitative), → accounts for multiple levels and temporal scales of GESs,	**Chapters 3** and **4**; papers 1 and 2

	→ provides a comprehensive approach to investigate linkages between management and GESs. The chosen concepts provide important and valuable underlying principles to foster the framework as an analytical approach, whereby adaptive management can be seen as a concept facilitating the understanding of regime complexity and the requirements of dealing with uncertainties and system alterations. The concept of ecosystem services serves to structure the linkages and dependencies between GESs and human well-being. The institutional approach has the power to shape incentives in human exchange and collaboration, and contains mechanisms to control people's rights to use the environment and to further mediate the link between ecosystem services and the constituents and determinants of human well-being. The framework takes into account the relationship between groundwater regimes and GESs facilitating in-depth analysis. The structure of the framework was designed to capture both management action and performance, and the state of the SES. The framework embraces complexity and context-dependence rather than defaulting to simplistic, generic recipes and can be applied to diverse fields of research (e.g., water, forestry and fisheries).	
2	The comparison of vertical and horizontal integration criteria towards the sustainable management of GESs across the case studies, using the TSD and additional queries as a reference for analysis, revealed that the degree of integration varied between all three cases and produced different types of outcome. The following conclusions can be drawn: • Political and economic shifts open windows of opportunity allowing for new approaches to natural resource management on the one hand, and create a variety of complex challenges including altered resource use patterns and new constellations of land users and land owners on the other. • The level of stakeholder participation in groundwater management compared, for example, to that of surface water management is relatively low and unpopular. One reason for this is that	**Chapters 3.2.1** and **6.1**; paper 2

	the link between users and the resource is often not apparent and, because many benefits are public goods, the economic value of groundwater and its services frequently goes unrecognized (especially for regulating, supporting and cultural services). • At all levels, groundwater governance and management is challenged by geographic and political boundaries. Therefore, it proved essential that the knowledge and experience of actors from different levels be taken into account when shaping the management of GESs. • The integration of industrial engagement (such as agriculture and mining) in management and water policies represents a key requirement for groundwater conservation. International, national and regional groundwater policies are more effective if they are designed and implemented in a cross-sectoral process, avoiding contradictions, finding synergies and developing common strategies in order to maintain both economic activities and ecosystem integrity. • A higher degree of sectoral integration is difficult to achieve in areas ruled by a single sector, such as agriculture in the UGB. Although agriculture is significant for people's livelihoods, it is also crucial that governance and management activities take into account all sectors, including also the different GESs without an explicit market (e.g. base flow, aesthetic beauty). The results of research topic 2 indicated that higher degrees of vertical and horizontal integration foster sustainable groundwater management and raise the awareness for different GESs.	
3	The empirical research conducted on the institutional response and integrative perspectives governing GESs provided crucial insights into the complexity of governance with respect to environmental problems. Institutional responses within the context of the individual case studies were triggered by a diverse set of drivers of change. Ecological drivers were dominant in all three case studies, triggering a basic rethinking of the role of GESs in formal and informal institu-	**Chapters 3.3, 6.2** and **supplementary study**

	tions. The effectiveness of institutions is greater where institutions incorporate multiple regulatory provisions and measures to support their effective implementation. Institutions must incorporate a capacity to include the social, economic and ecological perspective, and different requirements of groundwater use and protection. Some general trends with respect to institutional response were observed. Provisioning services were favored over regulating and cultural services across the case studies. Two general concerns became apparent: (i) institutional response is still at an early stage in terms of incorporating integrative perspectives of GESs and (ii) having well-crafted institutions in place does not automatically lead to successful groundwater management in the sense of bringing about positive results for social, economic and ecological sustainability. It became evident that institutions do not have to be developed by governments to be effective. Bottom-up approaches in the case studies showed that the initiative to protect different GESs is often more effective if local actors set up rules and implement them.	

The findings presented in the thesis fit into the overall debate surrounding adaptive water management that began in the early 2000s as an approach taking complex SESs into account during policy development and implementation. As reflected in different research projects (e.g., HarmoniCOP 2002-05, Millennium Ecosystem Assessment 2001-05, NeWater 2005-08) and institutional settings (e.g., South Africa's Water Act 1998, EU WFD 2000, EU Groundwater Directive 2006), public participation and cross-sectoral integration approaches have complemented traditional management practices in increasing the legitimacy and effectiveness of management and policy measures (Knill and Lenschow 2000, Huitema and Becker 2005, Engle and Lemos 2010). However, the implementation of new approaches faces several challenges in many countries around the world and the state of the resources remains endangered.

As the focus of the analysis covered a time horizon of more than 20 years, it was possible to discern a basic rethinking in the field of groundwater ecosystem management, and the fact that the significance of ecosystem services became more pronounced was reflected in diverse institutional settings. Cooperation and integration, stakeholder participation and exchange of information between different hierarchical levels increased in all three case studies and were reflected in different formal and informal institutions.

7.2 Critical reflection on the research

In this chapter a critical reflection on the conceptual research design underlying the research and the methods used to investigate the groundwater regimes that govern ecosystem service linkages and the related trade-offs is provided.

The deliberation of these issues underpins the need for further research in the overall context of groundwater resources management and ecosystem services. Finally, recommendations for additional steps to take this work forward beyond the scope of the research presented here are made.

7.2.1 Reflection on the conceptual research design and methods

A case study-based research approach was adopted to study potential relationships between groundwater regimes and the state of GESs. This approach offers analytical strengths, but also some weaknesses in relation to complex systems research (**chapter 4.1**). On the one hand, the case study approach provided for in-depth empirical evidence of major aspects crucial to addressing the research questions. It allowed the author to draw on the expertise and experience of regional groundwater experts, who are confronted with governance arrangements and groundwater – whether consciously or not – in their daily work.

On the other hand, the collection of case study data was time-consuming, and the comprehensiveness of the data set (covering a multitude of actors, institutions and GESs) proved challenging in the analysis. For example, the identification of the actors involved in groundwater management in each case study resulted in over 60 individual actors or actor groups, and the number of relevant institutions exceeded 50 in certain cases. Hence, the level of detail in the formalized case study representations must be chosen carefully so as to avoid the generation of an unmanageable data set, while still being detailed enough to do justice to the within-case complexity and to facilitate investigation. Therefore, an analytical approach supporting the aims of the research and the comparison of groundwater regimes was chosen. This approach built upon the MTF, which was specifically adapted to support a systematic and consistent investigation of groundwater policy and management processes.

The operationalization of the case study-based approach was accomplished through the TSD and specific queries, which were developed to explore and help understand links between the characteristics of an adaptive groundwater regime (here vertical and horizontal integration) and the impacts on GES linkages and trade-offs. A standardized means of data collection and analysis allowed for a high degree of consistency and consequently increased the validity of the results. Due to the shared language, the TSD facilitated the mapping and comparison of case studies and their individual contextual conditions by using the same categories for empirical variables and the same criteria for defining them.

Working with the MTF and the TSD required a sound understanding of the underlying principles of the database. It was also necessary to select carefully the case study experts for the interviews. The cooperation between the author and the case study experts relied on a high degree of trust and trustworthiness. This became particularly evident in Spain and South Africa, as the authors' cultural background and native language differed from the interviewees.

Another challenge relating to communication and cooperation concerned the terms chosen to define the components and underlying concepts of the MTF. The identification of a sequence of ASs in the respective case studies including all relevant class elements (i.e. actors, institutions, management processes and outcomes, and their relationships) required sufficient preparation time prior to the interviews to familiarize the regional experts with key terms used. Additionally, the concept of ecosystem services in general, and GESs in particular, turned out to be a relatively unknown issue for many of the interviewees, especially in the political arena of groundwater management. Therefore, the interviewer had to be sensitive to communication problems that arose during the interviews when the case study experts were not familiar with certain terms or concepts.

Working with the MTF consolidated different experiences and research insights. In comparison to other case study research - in the context of adaptive water management - using the MTF as a methodological and analytical approach:

- allows for a systematic analysis of complex governance regimes,
- supports the analysis of specific adaptive structural features of governance regimes (e.g., multi-level interactions) and maps dynamic management processes,
- demands large quantities of data and high quality data and its application is, therefore, time consuming.

These statements are underpinned by experiences made by other researchers (e.g., Bisaro et al. 2010, Knieper et al. 2010, Sendzimir et al. 2010, Schlüter et al. 2010). Over the course of the study it became apparent that the MTF must be further developed to investigate the relationship between the overall management system on the one hand and the actual ecosystem behavior on the other. Detailed recommendations for development are provided in **chapter 7.2.3**.

7.2.2 Reflection on the results

As mentioned previously, case study results offer limited possibilities in the analysis of cross-case variations, and it can be difficult or even impossible to replicate case studies to confirm their findings (Poteete et al. 2010). However, the results of this study provided new insights and ways of thinking, which have a validity not entirely dependent upon the cases from which they were drawn.

The main goal of the research was to identify relationships between groundwater regimes and GESs; in other words, management impacts on ecological processes and functions in the groundwater context. Vertical and horizontal integration and institutional responses were used as the guiding characteristics to analyze adaptive groundwater regimes. Although the results cannot be applied to all countries around the world, some can be transferred to other cases with similar contextual conditions (e.g., climate conditions, population size, economic development, and social standards and norms) and used to support the identification of 'lessons learnt' with respect to governance failure and success. These results can be summarized under two headings:

<u>Higher degrees of vertical and horizontal integration</u>:

- open up the political arena to environmental perspectives
- increase the quality of groundwater and conservation plans
- accelerate the implementation of policies
- mitigate conflicts between different groundwater users
- increase the awareness of different ecosystem services

<u>Development of institutional response</u>:

- still in the early stages of incorporating integrative perspectives of the different benefits GESs provide
- the mere existence of well-crafted institutions is not sufficient to produce socially, ecologically or economically satisfactory results

Originally it was intended to detect direct linkages between the groundwater regime, its performance and the impacts on GESs. It became apparent, however, that additional research techniques and approaches are required to evaluate this complex relationship. Hence, the results do not reflect how the state of GESs changed over time, or how the specific hydrological and physical characteristics of an ecosystem altered within a specific case study. The following chapter provides recommendations for further research to tackle this challenge.

7.2.3 Recommended study improvements and the outlook with respect to future research

The analysis of vertical and horizontal integration and the investigation of the role of formal and informal institutions governing GESs captured important features of an adaptive groundwater regime (see **chapter 7.2.2**). The framework applied was developed especially to analyze these features, and would appear to be useful for follow-up research into natural resource management and ecosystem services. Further steps are required to examine the potential and the limitations of the novel framework, and to increase the number of applications to case studies around the world. The framework may be applied not only to the exploration of water management regimes but also to different areas of natural resource management such as forestry and fisheries.

Although the study revealed that groundwater ecosystem management benefits from vertical and horizontal integration structures (**chapter 6.1**), direct impacts on GESs (e.g., chemical and hydrological characteristics, biodiversity) were hardly explored. Although the main research objective of this thesis was to investigate groundwater regimes impacting GESs, it became apparent that it is difficult to detect clear links between these processes which can be related to appropriate time and space horizon chosen for the analysis (**chapter 6.1.3**).
One must be open about using quantitative modeling and research approaches in addition to qualitative research methods with regard to physical and hydro-geological alterations of GESs. In other words, morer mixed-methods are required for in-depth analysis of diverse case studies. Further research on the impacts of management is required, including empirical studies of natural conditions and their effects on human well-being.

To date, the typical situation in relation to groundwater management is that (i) diagnostic data are limited, (ii) use patterns involve a substantial number of individual abstractors, (iii) impacts are often delayed and not clearly visible, and (iv) damage to the resource can have long-term consequences (UNESCO 2006). Hence, there is a pressing need to amend the MTF for the specific analysis of ecological processes and functions and their alterations over time in order to provide adequate policy advice. To fill this research gap, the MTF must cover physical and ecological characteristics (e.g., soil formation, biodiversity, water quality and chemical status, etc.) in a more detailed way. One way to do this is to extend elements of the MTF class diagram and adapt the TSD:

- Amendment of further class attributes of the *water system*, *ecological system* and *ecosystems services* in order to detect linkages and system changes (e.g., land use patterns and ecological consequences),

- More precision with respect to the class *ecosystem services:* identification of trade-offs and linkages under climate and global changes (including temporal and spatial ecosystem service alterations),
- Arrangement of a chronological order of the ecosystem state (similar to the development of ASs).

So far, the efforts that have been made towards adaptive and sustainable management in the context of groundwater and associated ecosystem services, while laudable in many regions of the world, still need to be intensified and expanded. This is particularly important in countries dealing with challenges and uncertainties in relation to changing climate (e.g., increase in extreme events, such as droughts and floods), unevenly distributed water resources in terms of quality and quantity, rapid expansion of economic activities, population increase and problems associated with urbanization, inadequate access to fresh water or sanitation and insufficient health standards among other things.
The following research questions remain important in order to better understand and to address GES management challenges, both social and ecological:

- Who determines which ecosystem services should be prioritized for protection?
- What components of these services should be valued?
- How do ecosystems and their services change over time, and what are the major consequences for human well-being in both developed and developing countries?

Finally, difficulties in detecting relationships between groundwater regimes and GESs make a large empirical base of cases necessary to facilitate the generation of more general theories on how these structures are related to sustainable resource management. Given the increasing trend towards environment policy building on the concept of ecosystem services, it would be beneficial to investigate whether this concept can be used to communicate management challenges in which researchers and water managers must take into account human and biophysical characteristics as intertwined systems.

7.3 Closing comment

I want to close this thesis with a statement made by Carpenter et al. (2009). This statement expresses the challenges researchers have to deal with in finding answers to explain and understand complex SESs.

"*In any particular situation, available options must be evaluated, selected, implemented, tested, and then replaced or modified in an ongoing search for better outcomes. Global rehabilitation of ecosystem services and human well-being is therefore a long-term, spatially complex experiment that requires continuous innovation and learning.*
To this end, it is imperative that the policy and science communities establish a capacity to create and implement policies for SESs, predict consequences and evaluate outcomes. Research on SESs must be expanded to build this capacity, and more appropriate, integrate approaches to research must be developed."

I hope this piece of interdisciplinary research contributes to new insights and knowledge in the realm of GESs and complex governance and management regimes.

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Appendices

A) The original class diagram of the management and transition framework

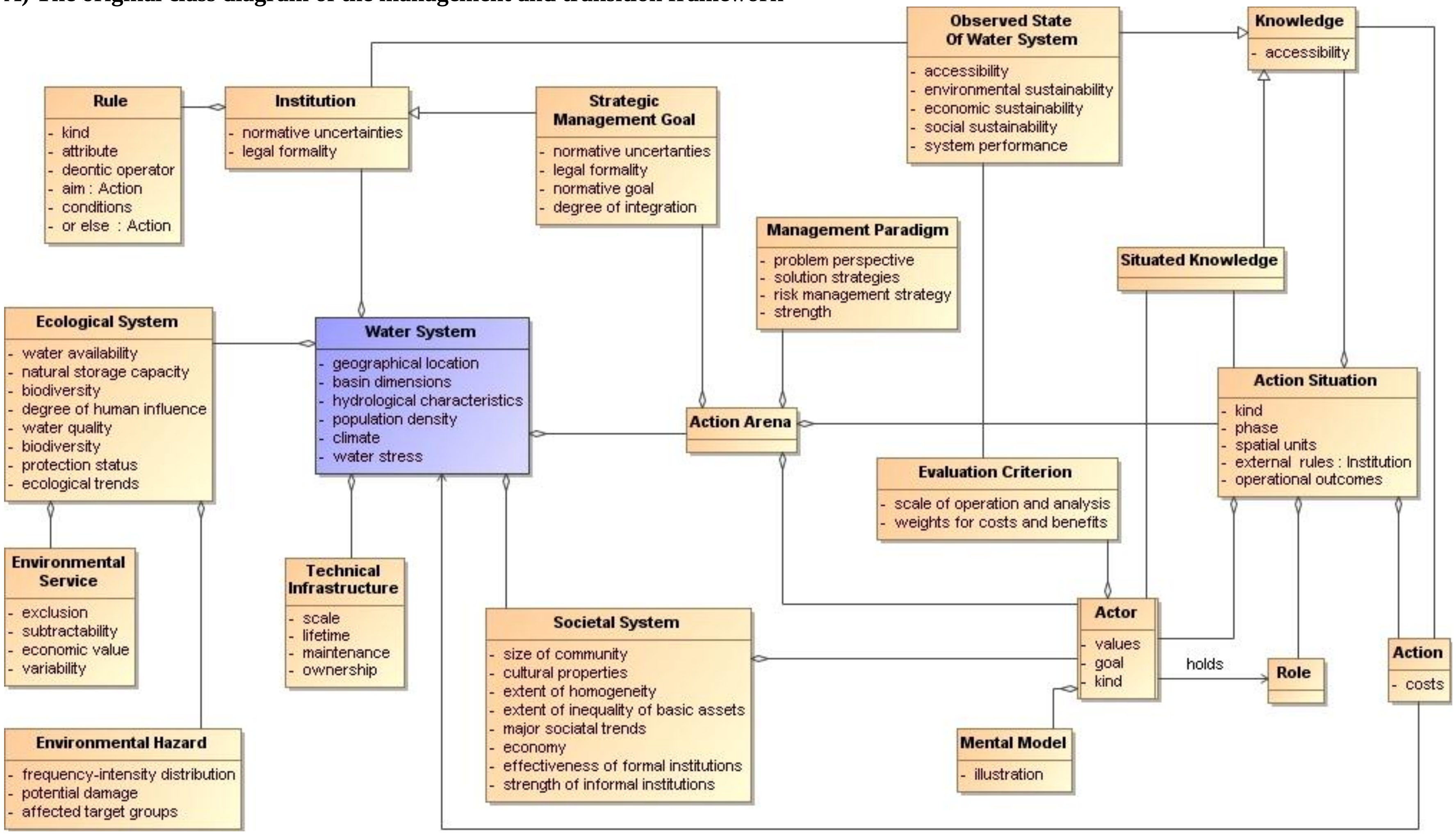

Figure 8 Class diagram of the management and transition framework

B) Management and transition framework: classes and attributes

Table 13 Class elements and attributes

Class element	Explanation	Attributes
Water system	The water system is the highest and most aggregated class comprising all environmental and human components.	Geographical location, basin dimension, hydrological characteristics, population density, water stress index
Socio-economic system	The socio-economic system is shaped by cultural, political, historical, religious and spiritual context-specific attributes. In general, the socio-economic system refers to national or regional boundaries as many of the attributes characterizing the context are determined by and for administrative boundaries (e.g., legislation, economic growth).	Size of community, human development index, cultural properties, economy (GDP), role of institutions
Ecological system	The ecological system comprises abiotic and biotic components of the groundwater body and related ecosystems such as floodplains, swamps, springs and sloughs. In very large aquifer systems there is likely to be more than one ecological system.	Water availability, natural storage capacity, degree of human influence, water quality, biodiversity, ecological trends
Groundwater ecosystem service (GES)	GESs frame the interface and the bridging element between the ecological system and socio-economic system and serve as a resource for human beings.	Excludability, subtractibility, economic value, degree of variability
Environmental hazards	Environmental hazards (e.g., drought, flooding) are sporadic natural events with severe impacts for the ecological system and socio-economic system.	Frequency-intensity distribution, potential damage, target groups affected
Action arena	An action arena can be linked to ASs or actors and refers to different policy sectors and contexts related to the management of GESs: water supply, flood protection, drought prevention, water pollution control, fisheries, agriculture, energy, tourism, spatial planning, nature protection, water ecosystem management,	No relevant attributes

	etc.	
Action situation (AS)	An AS is a structured social interaction context (e.g., a step in water management or in a policy process) that leads to specific outcomes. Outcomes can be institutions that affect social interactions in other ASs or operational outcomes, which are direct interventions in the system.	Policy phase, kind*:* constitutional, collective choice, operational (according to the institutional analysis and development framework)
Spatial unit	The spatial unit refers to a specific level (e.g., Germany, Brandenburg, Spree basin).	Administration level: international, national, regional, local, basin, sub-basin
Actor	Actors are individuals or organizations who participate in different water management processes.	Governmental or non-governmental, individual or collective, values (economic, social, ecological), goals (main targets of the actor)
Institution	Institutions are considered to be "*a set of rules, decision-making procedures, and programs that define social practices, assign roles to the participants in these practices, and guide interactions among the occupants of individual roles*" (Young 2002). Examples of institutions are water directives, plans, agreements between actors and informal social norms.	Legal formality (formal, informal but documented, informal and undocumented), affected system component: socio-economic system, ecological system, GESs
Operational outcome	An operational outcome is a concrete physical, measurable effect of groundwater management (e.g., land use change, composition of water chemistry, groundwater table drop).	Affected components: socio-economic system, ecological system, GESs

C) Overview of organizations and agencies chosen for qualitative interviews

Table 14 Organizations and agencies chosen for the qualitative interviews

Organizations and agencies	Date
South Africa	
University of KwaZulu Natal, Pietermaritzburg	04.12.09
University of KwaZulu Natal, Pietermaritzburg	02.12.09
University of KwaZulu Natal, Pietermaritzburg	02.12.09
University of KwaZulu Natal, Pietermaritzburg	03.12.09
Council for Scientific and Industrial Research, Pretoria	02.12.09
University of Witwatersand, Johannesburg	04.12.09
Regional Department of Water Affairs (Northern Cape), Pretoria	07.12.09
National Department of Water Affairs, Pretoria	07.12.09
National Department of Water Affairs, Pretoria	07.12.09
Council for Scientific and Industrial Research, Pretoria	08.12.09
Council for Scientific and Industrial Research, Pretoria	08.12.09
Water Resource Commission, Pretoria	09.12.09
Water Resource Commission, Pretoria	09.12.09
National Department of Water Affairs, Pretoria	09.12.09
South African National Biodiversity Institute, Pretoria	10.12.09
Water Geosciences Consulting	10.12.09
Water Resource Commission, Pretoria	14.12.09
Agri Informatics, Stellenbosch	06.08.10
Yara South Africa, Sandveld	06.08.10
Northern Sandveld Water User Association, Sandveld	06.08.10
Geohydrological and Spatial Solutions International (Pty) Ltd), Stellenbosch	10.08.10
Western Cape Nature Conservation Board, Paarl	12.08.10
Regional Department of Agriculture, Stellenbosch	12.08.10
Potato SA, Sandveld	13.08.10
Agri Informatics, Stellenbosch	07.02.11
Yara South Africa, Sandveld	07.02.11
Geohydrological and Spatial Solutions International (Pty) Ltd), Stellenbosch	08.02.11
Potato SA, Sandveld	11.02.11
Informage, Worcester	09.02.11
Regional Department of Water Affairs (Western Cape), Stellenbosch	10.02.11
Germany	

The Berlin-Brandenburg Academy of Sciences and Humanities, Berlin	12.11.10
Grüne Liga Berlin e.V., Berlin	12.11.10
Consultancy office for hydrology	15.11.10
Ministry of Environment, Health and Consumer Protection of the Federal State of Brandenburg, Cottbus	29.11.10
Office of the Biosphere Reserve *Spreewald*, Lübbenau	30.11.10
Project office *Gewässerrandstreifenprojekt*, Lübbenbau	30.11.10
Forestry office, Lübben	01.12.10
Brandenburg University of Technology, Cottbus	02.12.10
Ministry of Environment, Health and Consumer Protection of the Federal State of Brandenburg, Cottbus	03.12.10
Ministry of Environment, Health and Consumer Protection of the Federal State of Brandenburg, Cottbus	03.12.10
Spain	
Universidad Politécnica de Madrid, Madrid	09.01.11
Universidad Politécnica de Madrid, Madrid	09.01.11
Universidad Politécnica de Madrid, Madrid	10.01.11
Universidad Politécnica de Madrid, Madrid	10.01.11
Área Planificación Ambiental, Tecnoma	11.01.11
Universidad Complutense de Madrid, Madrid	11.01.11
Confederación Hidrográfica del Guadiana, Ciudad Real	12.01.11
Confederación Hidrográfica del Guadiana, Ciudad Real	12.01.11
Fundación Nueva Cultura del Agua, Madrid	13.01.11

D) Queries

Table 15 Database queries

Relations
Institution -> affected basin component
Operational outcome -> affected basin component
Ecological system -> environmental hazard
Ecological system -> GESs
Environmental hazard -> institution
GESs -> institution
Basics properties
Basic_AS_basicProperties This query gives a general overview of all AS: name, level, lead, number actors involved, kind, phase
Basic_NrActors_perSpatialUnit Shows for each spatial unit how many actors are located on that level (based on actor attribute 'spatial unit')
Basic_NrAS_perSpatialUnit Shows for each spatial unit how many AS have been identified on that level (based on AS attribute 'spatial unit')
Basic_AS_kindOnLevels Shows for all levels how many AS of each kind (according to IAD) are identified
Basic_AS_phaseOnLevels Shows for all levels and phases how many AS are located on that level and in that phase
Basic_countActorsRoles The role adopted by each actor and how often is shown. The actor's spatial unit, administrative level and type are also shown. In the case of a collaborative actor, the participating actors are listed
Networks of action situations
ASNet_AS_influencedBy_institution or knowledge or operational outcome Lists all pairs of {AS, institution or knowledge or operational outcome} with AS being influenced by the institution or knowledge or operational outcome
ASNet_AS_produces_institution or knowledge or operational outcome Lists all pairs of {AS, institution} with AS producing the institution or knowledge or operational outcome
ASNet_ASproduces_institution(or knowledge or operational outcome)_ influencesAS Lists all triplets {AS1, institution or knowledge or operational outcome, AS2} in which AS1 produces institution or knowledge or operational outcome and institution or knowledge or operational outcome influences AS2
ASNet_perInstitution (or knowledge or operational outcome)_ASProd_ASInfl Lists for all institutions (or knowledge or operational outcome) the AS that produce this institution (or knowledge or operational outcome) or are influenced by this institution (or knowledge or operational outcome) (not showing spatial units and administrative levels)
Vertical integration

VI_actors_participateOnLevel Shows for each actor the actor's own level as well as all levels on which the actor participates in an AS. This query can be used to identify actors active on multiple levels and is, therefore, important for vertical integration	
VI_actors_participateOnLevel_withRole This query shows for each actor the actor's own level as well as all levels on which the actor participates in an AS and the role the actor plays on that level	
VI_actors_participateOnLevel_NrASperLevel Shows for each actor the actor's level and for each level on which he participates the number of AS in which he participates (on that level, directly or through collaborative actors)	
VI_actors_participateOnLevels_NrLevel Shows for each actor the level as well as the number of levels on which the actor participates in AS (directly or through collaborative actors)	
VI_AS_actorsFromLevelInvolved Shows for each AS the AS level as well as all levels from which actors participate in this AS. This shows whether some levels are more prominent in bringing together actors from multiple levels and gives an overview on the broadness of participation in the sense of the number of levels from which actors are involved	
VI_nonGovActors_perAS Shows for each AS its level, its kind and the number of governmental and the number of non-governmental actors involved. The query only considers individual, collective and aggregated actors. Collaborative actors are 'open-end', i.e. treated as if the actors participating as collaborative actors would be participating directly in the respective AS	
VI_nonGovActors_directly_perAS_roles For each AS and each combination of {actor is gov/non-gov, actor's role} the number of respective actors in this AS is given (e.g., 1 actor who is governmental and has the lead, 2 actors who are governmental and active, 5 who are non-governmental and passive, etc.). The query only considers direct participation of actors in the AS, i.e., participation via collaborative actors is not considered	
VI_participationInGeneratingAS_institutions (or knowledge or operational outcome For each pair of AS {AS1, AS2} for which AS1 produces an institution which influences AS2, the number of actors involved in both AS1 and AS2 is shown to check Ostrom's principle that actors who are influenced should also participate in design (of institutions / operational outcomes). It further shows the total number of actors in AS2 and AS1	
Horizontal integration	
HI_AA_occurences Counts the number of times an AA occurs in the TSD. This gives an initial overview of the integration of different sectors in the topic for which data was collected	
HI_AA_occurences_perLevel Same as SI_AA_occurences but differentiated for levels. This may indicate on which levels certain sectors are considered	
HI_actors_involvedInNrAA Shows for each actor the number of different AAs this actor is involved in (via AS). The spatial unit of actors is also given. This query shows how AA are possibly integrated via actors	
HI_AA_linkedToAS_numberPerAS Shows for each AS its level and the number of AAs directly linked to this AS (i.e., not (only) via actors)	

HI_AS_numberAAViaActors
Shows for each AS the number of AAs linked to this AS via actors involved in this AS
HI_AS_numberOfActorsFromAAInvolved
Shows for each AS the number of actors from each AA involved in this AS.
HI_AS_numberOfActorsFromAAInvolved_roles
Similar to SI_AS_numberOfActorsFromAAInvolved but groups according to actors' roles, i.e., it shows for each AS the number of actors from a specific AA having a specific role

E) Action situations in the three case studies

Table 16 Overview of all action situations identified in the case studies

SANDVELD		
No.	**Action situation**	
A AS1	**Late 1980s** The Sandveld received access to electricity	Access to electricity resulted in an increased number of wells and greater water abstraction rates. Many GESs were traded-off, basically regulating services (e.g., base flow to wetlands) and cultural services due to intensive land clearing for agriculture production.
A AS2	**1990** Official declaration of over-exploitation of the Sandveld aquifer	The unsustainable groundwater development was recognized by the DWA, resulting in the declaration of the Sandveld aquifer. For irrigation, a quota of 5 000 m^3/ha was established without any impact on GESs. Due to insufficient control and a lack of monitoring. Groundwater management was still unsustainable in terms of abstraction rates and land clearing.
A AS3	**1998** Enactment of South Africa's National Water Act (NWA)	Progressive and innovative framework for water governance and management in South Africa. Demands a decentralization of water management and active participation processes. The act includes the principles of equity, efficiency and sustainability in the allocation of all water resources. 13 years after promulgation, effective implementation remains a challenge in the Sandveld due basically to a lack of human and financial capacities. A AS4-7 are outcome of this AS.
A AS4	**2000-04** Integrated Water Resources Management (IWRM) phase I	The South African DWA, with the assistance of the Royal Danish Government, initiated a program in 2000 to pilot IWRM approaches. This program developed a number of guidelines related to groundwater, water conservation and demand management, and provided support to water management institutions. It achieved awareness of the importance of groundwater and the protection of GESs.
A AS5	**2006-10** IWRM phase II	IWRM phase II built upon the experiences of IWRM phase I. Groundwater and water reforms were a very important element of phase II. Commercial and emerging farmers in the Sandveld were educated and trained for groundwater issues.
A AS6	**2005** Establishment of Catchment Management Agency (CMA) Proposal	The CMA Proposal was prepared under the terms of Section 77 of the NWA in order to achieve a decentralization of water management in the Olifants/Doorn Water Management Area. No direct impacts on GESs but in terms of sustainable resources management the establishment of the proposal was carried out in an active participative process. As yet, there exists no CMA in the respective catchment.
A AS7	**2007**	The WUA is a newly formed association with the task of managing water resources at sub-basin level. The Sandveld

	Establishment of the Sandveld Water User Association (WUA)	WUA has no influence on water management issues and is not involved in governmental decision-making or planning.
A AS8	~**2000** Hydro-geological exploration of the Sandveld area	Exploration of the Sandveld includes aquifers, vegetation cover and landscape water regime. The understanding of GEs processes and functions improved and 'theoretically' provide a frame for the basis for sustainable groundwater management.
A AS9	**2000** Announcement of the C.A.P.E. Strategy	This biodiversity program had its foundation in NGO-moderated planning exercises and has become a core element of environmental governance in South Africa. C.A.P.E. is a governmental program developed with various experts and stakeholders. It pushed forward new strategies for nature protection and biodiversity in the Cape region of South Africa and achieved ecological awareness nationwide.
A AS10	**2004** Establishment of Greater Cederberg Biodiversity Corridor (GCBC)	The principle goal of the GCBC is to maintain and restore connectivity across landscapes. To achieve this, the GCBC aims to stimulate the creation of additional protected areas through voluntary stewardship agreements, the introduction of more sustainable land use strategies and the restoration of degraded landscapes. The Sandveld Core Corridor is of the highest conservation priority due to the high rate of natural land transformation to agricultural land use including intensive water abstraction rates. The aim of the corridor is to improve protected area management, build management capacity.
A AS11	**2006** Implementation of the GCBC Biodiversity Stewardship Program	This program encourages landowners to voluntary join partnerships with CapeNature in order to achieve conservation in the Sandveld: expansion of protected areas by setting limitations on certain land use practices, decrease in the irrigated area and expansion of natural flora and fauna habitats.
A AS12	**Late 2006** Ministerial visit to the Sandveld	Due to bad media and pressure by the broader public regarding unsustainable farming practices and illegal practices, the Minister (Department of Environmental Affairs) visited the Sandveld. An action plan was developed to support the interests of local stakeholders and the broader community. The Sandveld area became a hotspot of interest. Farmers and official actors were put under pressure. The Action Plan for the Sandveld set new standards for farming in order to protect water resources and the environment. A AS13-14 are outcome of this AS.
A AS13	**2006-07** Implementation of Biodiversity and Business project	The Biodiversity and Business project and the GCBC initiative have taken a coordinated approach to link the projects to existing stewardship activities. Producer farms that are participants in the Biodiversity and Business projects have been earmarked for stewardship negotiation where farmers' property forms part of the Sandveld Core Corridor and contribute to the conservation of priority biodiversity.
A AS14	**2006-07**	Groundbreaking project in the Sandveld mainstreaming biodiversity into the agriculture production sector. The draft-

	Drafting of biodiversity best practices for potato production (BPP)	ing of the BPP was pushed forward by a multi-stakeholder process including industry, farmers, governmental agencies, conservation groups and local stakeholders.
A AS15	**Late 2007** Implementation of the BPP	Farmers started to implement BPP under the supervision of CapeNature. In the beginning, BPP was implemented by farmers voluntarily. The world watched the Sandveld with interest because it is rare for farmers and retailers to work with the government to implement conservation on privately owned land voluntarily.
A AS16	**2009-10** Evaluation of BPP	Specific evaluation criteria of measurements (scoring systems) were developed to identify the success or failure of BPP implementation. Some elements of the BPP do not fulfill the requirements of the National Environmental Management Act. The failure to comply with these requirements meant disqualification as a 'Best Practice Producer'.
A AS17	**2010-present** Development of a Joint Enforcement Strategy	In order to overcome contradictions between BPP and the National Environmental Act a Joint Enforcement Strategy was developed and is currently under review. To further implement the BPP and achieve sustainable agriculture practices, the Joint Enforcement Strategy is currently under review at national and regional departments.
UGB		
No.	**Action situation**	
B AS1	**1985** Enactment of the new Spanish Water Act	The Water Act radically transformed the institutional context of groundwater management in Spain. From this point on groundwater is a public good but traditional property rights are still respected. Users can choose to register their rights as private uses and transform them into administrative concessions. RBA acquired jurisdiction over groundwater and existing wells have to be registered. However, many wells remain illegal and water is still considered private by many farmers. The Water Act was amended in 1999.
B AS2	**1991** Declaration of overexploitation of Western Mancha aquifer	The Western Mancha aquifer was declared overexploited by the Guadiana RBA and water abstractions were subject to specific restrictions placed on irrigators. Enforcement of this legal provision has proven to be inefficient due to the strong legal and practical opposition from the irrigators and the consequent high transaction costs involved for control and administration.
B AS3	**1991** Implementation of water abstraction plans (WAP)	Yearly pumping restrictions (pumping quotas) without economic compensation payments. Pumping restrictions were highly unpopular in the UGB, as they triggered significant negative consequences for farmer incomes.
B AS4	**1993** Implementation of the Agro-Environmental Program (AEP)	The AEP is an EU funding program and essentially conceived to reduce water withdrawals by means of compensatory subsidies. Farmers were offered the option to cut water use by 50 %, 70 % or 100 %. Most farmers chose the second option, receiving subsidies in the order of €300/ha. Aquifer levels started to recover. B AS5 is an outcome of this AS.

B AS5	**2003-07** Modulation of AEP	The AEP is modulated; the amount of water granted is adapted to the pumping quotas (new calculations were related to the requirements of WAP). For this second phase of the AEP only the 50 % and 100 % were considered. Payments now based on farm size. Consequently, farmers with large farms receive lower payments. Many farmers leave the program, abstractions increase and aquifer levels decrease.
B AS6	**2000** Legal implementation of the WFD	The WFD is the most relevant water policy initiative of the last 20 years in the EU; perhaps the most advanced international initiative based on world standards. Mandates of the WFD include: water pricing, ecological objectives, political processes, public participation and new approaches to water planning. The WFD implies a rebalancing of priorities from ensuring water supplies to all economic users to improving the ecological status of all water bodies. The general goal is that all surface and groundwater bodies should achieve good ecological status by 2015.
B AS7	**2001** Approval of the National Hydrological Plan (NHP)	The central issue of the NHP is the regulation of water resources by transfer from catchments that have (so-called) water 'in excess' to catchments with a (so-called) 'water deficit', which is considered to be the best solution to satisfy water demands throughout the national territory. The plan has caused deep controversy in all sectors (political, social, environmental and technical) in Spain. The plan includes a mandate to develop a Special Plan for the Upper Guadiana Basin (SPUGB). A AS8-15 are the outcome of this AS.
B AS8	**2001-2003** Tajo-Segura water transfer	Diversion of flows from the existing Tajo-Segura pipeline through the River Ciguela into wetlands of the National Park *Las Tablas de Daimiel* (existing infrastructure was used). Results are controversial: the transfer does not address the real causes of wetland degradation and has some negative environmental consequences: invasive fish species, salinization, decrease in native vegetation. However, at least the wetlands survive in an artificial state ('ecological coma'). Farmers dispute the rights of the water transfer. Social conflicts between farmers, conservationists and the RBA have led to mistrust.
B AS9	**2001-02** Drafting of SPUGB proposal	As required by the NHP, the SPUGB was developed. The plan should seek solutions to protect the wetlands without negatively impacting upon the socio-economic development in the UGB.
B AS10	**2003** Official presentation of SPUGB	Official presentation of the first draft to official members and state bodies as well as major farmers and irrigation communities. After the official presentation the plan was presented to the public. First draft of the plan was rejected. Neither municipalities, the national park nor NGOs were informed or consulted during this process. Various allegations against the draft: no true participatory process during the elaboration of SPUGB.
B AS11	**2004** Seminar on the SPUGB	The seminar is an unofficial discussion forum initiated as a reaction to the SPUGB proposal. The seminar mainly comprises stakeholders left out during the development of the plan. The participants of the seminar demand a new formulartion process including all stakeholders.
B AS12	**2004-06**	A process of re-formulation of the SPUGB started. Turning point in 2004 due to new government elections. Man-

	Formulation of guidelines and new draft SPUGB	agement of water resources becomes more open and visible for stakeholders. The newly elected Guadiana RBA starts bilateral meetings to inform stakeholders and invite them to participate in the design of a new SPUGB.
B AS13	**2007** Submission of SPUGB for public review	The second draft of the SPUGB is presented – this time to a broader audience. A high level of agreement is achieved. Unfortunately, NGOs do not agree upon all measures of the SPUGB, although they do not start a campaign against the plan.
B AS14	**2008** Formal approval of SPUGB	The SPUGB is approved for the period 2008-2027 with a budget of €5 billion. Three years after the official approval of the SPUGB it still has not not implemented. With the current economic crisis in Spain, most of the money intended for the purchase of water rights has not materialized, and the only funding now likely to arrive is dedicated to the reforestation of land that has reverted to dryland farming after the purchase of water rights.
SPREE BASIN		
No.	**Action situation**	
C AS1	**1990** Re-unification of Germany	The German Democratic Republic (GDR/East Germany) joins the Federal Republic of Germany (FRG/West Germany). Lignite rapidly loses its monopoly status in the former East German states. Groundwater consumption for mining activities increases. A particular challenge to the development of water management is the repair and construction of a modern water supply and wastewater disposal in former East Germany. This requires the joint efforts of the nation, the municipalities, the federal states, and the economy in a national solidarity action with substantial financial means.
C AS2	**~ 1990** Closure of open pit lignite mines	Since the unification of the two German states in 1990, lignite mining is substantially reduced, and many lignite pits have been closed. Groundwater extraction declines to a third of previous rates and the volume of the groundwater deficit in the River Spree catchment contrasts with the deficient natural water resources of the region.
C AS3	**1990** Establishment of the National Park Program of the GDR	The Spreewald Biosphere Reserve is legally registered - shortly before German re-unification. During the establishment of this project the public is excluded and not kept informed. This triggers conflicts and mistrust. The situation worsens due to the social and economic impacts of the re-unification and the high rate of unemployment.
C AS4	**1994** Release of first project conception of the Spreewald Riparian Land Project (GRSP)	In order to establish the GRSP, a project conception for the Spreewald area is established and released. The overall goal of the project contains the conservation and restoration of the natural and typical landscape of the Spreewald with its characteristic species through the stabilization of the water balance. Stakeholders from Spreewald and the broader public are against this project and many conflicts arise. People are afraid to lose land and property rights, which impact upon their livelihoods.
C AS5	**1994-98** Manifold revisions to the	The revisions of the project conception take four years. The revisions and content of the project include a participatory process including all stakeholders and incorporate local knowledge of the Spreewald.

	first project conception	
C AS6	**1998** Official approval of GRSP	Official approval of the project and start of the development of different measures to maintain and protect GESs. The Association for the Spreewald Riparian Land Project is established to coordinate the project and represent different stakeholder groups. Budget: €12 million, financed by the federal government (72.5 %), the state Brandenburg (20.5 %) and the Association for the Spreewald Riparian Land Project (7 %).
C AS7	**2000** Legal implementation of the WFD	See UGB.
C AS8	**2001-03** Drafting of the Maintenance and Development Plan (PEPL)	The PEPL includes various ecological protection and socio-economic development goals as well as the maintenance of the cultural heritage of the Spreewald. High level of stakeholder participation and cooperation between state and non-state actors. A moderation team is consulted to steer the development process and to avoid conflicts between stakeholders.
C AS9	**2004-13** Implementation of hydrolog-ical conservation measures (PEPL)	These measures are implemented in the region of the Spreewald Biosphere Reserve. Improvement of water quantity and quality and enhancement of flora and fauna habitats. The project area covers 23 000 ha.
C AS10	**2007-12** Implementation of compen-sation measures as a legal requirement for the mining industry	The reason for the compensation measures was the continuation of the Cottbus Nord mining activities and the clo-sure of the Lakoma Lakes (SAC status). Various types of compensation measures including an area 11 km in length along the River Spree downstream of the Spreewald.
C AS11	**2008-present** Exploitations for new lignite mining areas	The Vattenfall Europe Mining AG starts to explore further areas for new lignite mining. Opposition and many con-flicts arise: ecological, cultural and social concerns. Official agencies try to mediate the conflicts between the mining industry and stakeholders. As the mining industry has strong political influence in Brandenburg, the exploitation continues.

F) Aggregation of action situations

Table 17 Aggregation of action situations

Case studies	Periods of action situations	Level	Vertical* integration	Horizontal** integration	Non-state actors***	Outcome	
						Institutions	Operational outcome
Sandveld	Access to electricity and the following ecological crisis (A AS1-2)	Sub-basin	↓	↓	↓	- Registration/licensing of water abstraction	- Intensive groundwater use - Increased number of wells - Degradation or loss of different ecosystem functions and processes - Dehydration of wetland
	Political regime shift initiated an institutional and national response towards integrated water management (A AS3-6)	Basin Sub-basin	→	↓	↓	- National Water Act - Public status of groundwater - Campaigns and programs to promote protection of groundwater - Decentralization of water management - Hydro-geological investigations - Ecological reserve calculations	
	Emergence of bioregional great-scale conservation programs (A AS7-9)	Regional	→	↑	↑	- Biodiversity stewardship farms - Formal conservation areas	- Expansion of protected habitats and landscape corridors - Rehabilitation of regulating and supporting GESs - Increased cultural services (for tourism and recreation purposes)

	Bottom-up approaches: mainstreaming biodiversity into the production sector (A AS10-12)	Sub-basin	↑	→	↑	- Biodiversity guidelines and environmental management plans for farmers - Control and monitoring of illegal water abstraction and land clearing	- Decreased irrigated surface area - Expansion of flora and fauna habitats - Drought buffer zones
UGB	Ecological crisis impacting farmer livelihoods and ecosystem integrity (B AS2)	Sub-basin	↓	↓	↓	- Drilling ban - Constitution of water user associations - Water abstraction plan	- Societal conflicts - Increased number of illegal wells and water abstraction
	International and national response to water scarcity and ecological damages (B AS3-5)	National	↑	→	→	- Income compensation payments for farmers to use less water for irrigation - Pumping restrictions (quotas)	- Partial recovery of the aquifers - Increase in less water-intensive crops - Increased farmers incomes - Societal conflicts
	Water transfer schemes (B AS7-8)	Sub-basin	↓	→	↓		- Partial recovery of the wetlands - Salinization - Decrease in native vegetation - Invasive fish species
	Special Plan for the UGB to maintain ecological integrity without impact on rural livelihoods (B AS9-14)	Sub-basin	→	↓	↑	- Purchasing of water rights - Socio-economic restructuring plan - Total budget of the plan: €5 billion	- Societal conflicts - Reforestation

Spree Basin	Political and economic regime shift as a window of opportunity for new water management approaches (C AS1-3)	National	↓	↓	→	- Economic collapse of mining industry - Establishment of Spreewald Biosphere Reserve - Environmental contracting	- Increased unemployment - Decreased water consumption - Increased groundwater level in mining areas (=water pollution) - Expansion of protected areas and maintenance of cultural heritage
	Spreewald Riparian Land Project: multi-stakeholder project to conserve and restore the landscape water system (C AS4-6)	Sub-basin	↑	↑	↑	- Compensation payments and land purchasing - Environmental contracting	- Societal conflicts - Increase in groundwater-dependent landscapes for highly adapted flora and fauna - Increased possibilities for recreation
	Conservation and development plan to maintain the natural and cultural heritage of the Spreewald (C AS8-9)	Sub-basin	↑	↑	↓	- Saturator requirements of the WFD and Federal Water Act (groundwater quality standards)	- Restoration and revitalization of running waters - Connection of oxbow lakes - Modification and creation of ecologically permeable structures - Reintroduction of periodic flooding in different areas
	Mining industry and legal requirements of nature protection (C AS10-11)	Regional	↑	↑	→	- Environmental assessment analysis (international standards) - Development of compensation measures	- Mining activities resume - Impacts on base flow to the River Spree and decreased water quality

(↓ low; → middle; ↑ high)

* The degree of vertical integration is calculated as ∑ of all levels involved in ASs / number of ASs belonging to a specific period

** The degree of horizontal integration is calculated as ∑ of number of AAs presented by different actors / number of ASs belonging to a specific period

*** Number of all non-state actors involved in specific periods of ASs

G) Role of institutions in social-ecological systems

Table 18 The role of institutions including their regulatory provisions and measures, the degree of implementation as well as their effectiveness on groundwater ecosystem services

Institutions	Regulatory provisions and measures	Implementation	Environmental effects	Societal effects
Sandveld				
National Water Act (1998)	- Registration/licensing of water abstraction - Ecological reserve - Decentralization of water management	Partly	- (Temporary) reserve calculations	- Establishment of Northern Sandveld Water User Association - Still no catchment management agencies
National Groundwater Strategy (2010)	- Hydro-geological mapping - National groundwater database - Groundwater reserve	Hardly	No measurable effects as yet	
Greater Cederberg Biodiversity Corridor	- Landowner database - Area-wide planning	Partly	- Expansion of protected areas - Re-establishment of flora and fauna habitats	- Industry engagement and local economic development - Education and rising awareness

Biodiversity best practices for potato production	- Environmental management plan
	  ○ Guidelines for soil, irrigation, fertilizer, and integrated pest management
	  ○ GIS reference maps
	  ○ Financial planning
	- Accreditation of good agricultural practice
		Partly	- Efficient irrigation techniques
			- Water savings
			- Decreased fertilizer and pesticide use
			- Buffer zones
			- Clearing of alien invasive plants
				- Industry engagement
				- Multi-stakeholder process
				- Many farmers join the program (voluntarily)

UGB				
Spanish Water Act (1985, amended in 1999 and 2003)	- Registration of groundwater abstractions - Official declaration of aquifer over-	Partly	- Not very successful in environmental issues - Mancha aquifer was declared	- Private and public rights co-exist in the same aquifer - Establishment of groundwater

	exploitation o Water management plans and yearly pumping restrictions		overexploited	user associations - Legal reaffirmation of public participation - Lack of educational and informational efforts by the main agencies
EU Agro-Environmental Program 1	- Voluntary water quotas and income compensation payments independent of farm size	Fully	- Lower water consumption - Modern irrigation techniques - Increase in low-water demanding crops - Recovery of the aquifer - Partial restoration of wetlands	- Large adoption rate by farmers - Sufficient compensation payments - Farm income gain - Social stability - Low cost-effectiveness
EU Agro-Environmental Program 2	- Voluntary water quotas and income compensation payments according to farm size (based on the pumping restrictions of the Spanish Water Abstraction Plans)	Hardly	- No recovery of the aquifer due to low implementation of the program - Illegal water abstraction	- Low adoption by farmers - Social unrest - Compensation payments insufficient - Farm income loss
EU WFD (2000)	Achieve good qualitative and quantitative status of all water bodies by 2015. - River basin management plans - Water pricing instruments	Partly, implementation until 2015	- Amelioration of the ecological conditions of watercourses - Lower water use in some areas	- Transparency and public participation - Accountability and cost effectiveness assessment of policy measures
EU Groundwater Directive (2006)	- Measures of water quality standards (e.g., nitrates, pesticides)	Hardly	No measurable effects as yet	
National Hydrological Plan	Special Plan for the Upper Guadiana Basin: - Purchasing water rights - Socio-economic restructuring plan - Reforestation plan - Extensive rain-fed farming	Hardly	- Reforestation of land	- High enforcement costs - Generation of rural employment - (Partial) purchase of water rights - Illegal water abstraction

				- Funding has not completely materialized
Spree Basin				
Federal Water Act of Brandenburg (2004)	- Water protection zoning - Sewage disposal plans - Pure retaining orders - Water management/framework plans	Fully	- Water protection zones increase groundwater quality and quantity	- Water pricing systems - Public participation, access to information - Decentralization of different tasks and responsibilities to various state and non-state agencies
Federal Nature Conservation Act of Brandenburg (2004)	- Network of interlinked biotopes o Spreewald Biosphere Reserve - Impact regulations; SAC impact assessment - Landscape programs and master plans	Fully	- Expansion of protected areas - Resettlement of rare species	- Compensatory measures for use restrictions (agriculture, forestry and fishing)
EU WFD (2000)	Achieve good qualitative and quantitative status of all water bodies by 2015. - River basin management plans - Water pricing instruments - Spree master plan	Partly, implementation until 2015	No measurable effects as yet	- Transparency and public participation - Accountability and cost effectiveness assessment of policy measures
EU Groundwater Directive (2006)	(see UGB)	Hardly	No measurable effects as yet	
Spreewald Riparian Land Project (2005-13)	Conservation and development plan - Development of a backwater system - Deconstruction of drainage systems, protection and creation of flood plains. - Reintroduction of periodic flooding	Partly, implementation until 2013	- Increased habitat creation and restoration - Increased flora/fauna - Improvement of surface-groundwater connections	- Multi-stakeholder process - Purchase of land - Compensation payments

Papers

Knüppe K, Pahl-Wostl C (2011) A framework for the analysis of governance structures applying to groundwater resources and the requirements for the sustainable management of associated ecosystem services. Water Resources Management 25(13): 3387-3411. doi: 10.1007/s11269-011-9861-7

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Supplementary Study

Analyzing institutional response in South Africa, Spain and Germany: What shapes governance of groundwater ecosystem services?

Abstract

Our daily lives depend on the provision of services by different ecosystems in which an important contribution is made by groundwater ecosystem services. Institutions play an important role in managing these services as they offer a major source of stability and strength in providing diverse ways of coping with change and uncertainties. Institutions can evolve as a strategic response to different drivers of change such as political regime shifts or ecological circumstances. This study investigates the role of institutions for the sustainable management of groundwater ecosystem services and analyzes its development over time. Institutional response and ecosystem services are viewed from a governance perspective embedded in complex Social Ecological Systems.
A profound understanding of institutions in different Social Ecological Systems requires comprehensive and interdisciplinary empirical research. Therefore, insights are derived from three case studies in South Africa, Spain and Germany in which institutional changes impact the state of groundwater ecosystem services. Despite case study-specific variations, we found that institutional response evinces certain common trends in which provisioning services are favored over regulating or cultural services. Evidence suggests that (i) institutional response is at an early stage of incorporating integrative perspectives of different kind of benefits groundwater ecosystem services provide and (ii) having well-crafted institutions in place are not sufficient to produce socially, ecologically or economically satisfactory results. This work made a significant contribution to interdisciplinary research in the field of groundwater and ecosystem services that builds the foundations for improving the management of Social Ecological Systems.

Keywords: institutions; groundwater; ecosystem services; governance and management regimes; case study research

1. Introduction

For centuries, groundwater has possessed a certain mystery because water below the surface is invisible and relatively inaccessible. Groundwater has often been regarded as a simple underground reservoir that supplied water either to people or to surface ecosystems (Seward, 2010). Today we are aware that groundwater produces multiple ecosystem services that are interrelated in complex dynamic ways. These ecosystem services are claimed and modified by competing actors (e.g. farmers, conservationists, municipalities) producing social and ecological trade-offs because improvements of some services come at the expense of others (Bennett et al., 2009). Important groundwater related ecosystem service trade-offs are those between agricultural production and water quality, land use and biodiversity, and water use and aquatic biodiversity (MA, 2005). Groundwater governance and management regimes have often disregarded trade-offs, and prioritized socio-economic development over maintenance of multiple types of ecosystem services. The term management refers to activities of analyzing, monitoring, developing, and implementing measures to keep the state of natural resources within desirable bounds while the term governance takes into account actors and networks that formulate and implement policies. Therefore, governance sets the overall rules under which management operates (Pahl-Wostl, 2009). Groundwater governance comprises, "the fulfillment of appropriate authority and promotion of responsible collective action to ensure sustainable and efficient utilization of groundwater for the benefit of humans and dependent ecosystems." This definition provided by Foster et al. (2009) makes clear that governance must view human and bio-physical systems as intertwined components by taking into account both human benefits and the maintenance of groundwater ecosystem services.

Management has recently begun to consider the environmental dimension of groundwater dependent ecosystems and sustainability became a paradigm guiding principle in water management. However, relatively little is known about the Social Ecological System dynamics and the institutions governing groundwater in different societies and their alterations over time (Moench, 2004; Mukherji and Shah, 2005).

Institutions are a crucial component of Social Ecological Systems. Socially, institutions shape the activities and behavior of humans. Ecologically they determine the flow of ecosystem services from ecosystems to humans. Broadly defined, institutions are the prescriptions that humans use to organize all forms of repetitive and structured interactions (Ostrom, 2005). Institutions are made up of (i) formal, legally binding constructions (e.g. directives, laws, conventions) created through official channels of governmental bureaucracies and enforced by state agencies and (ii) informal, mostly unwritten and non-codified constructions (e.g. socially shared rules, self-imposed regulations) developed and enforced outside of legally sanctioned and public channels (North, 1990; Pahl-Wostl, 2009). Institutions determine the behavior and roles of different actors. Actors can be either an individual (e.g. farmer, citizen) or a collective participant (e.g. conservation group, municipality, state department) building up societal systems and taking part in groundwater management and policy processes in which they hold individual goals and values.
While ecosystems are complex, heterogeneous and continuously evolving, institutions offer a major source of stability and strength. They provide diverse ways of coping with change and trade-offs to prevent threshold effects of ecosystems and natural resources.

Over the past decade, the number of scientific articles and research projects addressing ecosystem change and ecosystem services has grown enormously, particularly since the publication of the Millennium Ecosystem Assessment in 2005 (MA, 2005; Carpenter et al., 2009). Although a few studies have investigated the linkages between institutions and ecosystem services (e.g. Pritchard et al., 2000; Gómez-Baggethun and Kelemen, 2008; Ross and Martínez-Santos, 2009), we are unaware of explorative studies that have systematically investigated how institutions shape both the societal and environmental context of ecosystem services. We address this research gap, in the realm of groundwater ecosystem services by exploring the question: what are drivers of change and how did they impact institutional response towards integrative perspectives of groundwater ecosystem services for societal and environmental water needs?

To answer this question, we use a novel conceptual and analytical approach (Knüppe and Pahl-Wostl, 2011) – which builds upon the Management and Transition Framework (Pahl-Wostl et al., 2010). This approach allows a systematic and consistent representation of linkages between drivers of change, institutional response and the effects they have on groundwater ecosystem services over a certain period of time. This paper derives empirical evidence from three cases which went through periods of massive change including a continuous need for improvement and adaptation of groundwater institutions: Sandveld (South Africa), Upper Guadiana (Spain) and Spree (Germany).

2. The research design: framing institutional response

Groundwater managers easily overlook some critical linkages of Social Ecological Systems: societies affect ecosystems, the services they provide and environmental conditions and, likewise, ecosystems and environmental conditions impose constraints on, and provide benefits for societal development. It is rare to find a liner causal path between these linkages. Instead, causal patterns are much more complex and linkages may differ at particular locations or over particular time scales (Carpenter et al., 2009). Thus, managing groundwater resources in a sustainable, equitable and adaptive manner requires integrative perspectives on social and ecological systems; a coupled, inseparable system of humans and nature (Gunderson and Holling, 2002; Folke et al., 2005; MA, 2005). The following section views groundwater ecosystem services from an integrative perspective. Further, we design a novel conceptual framework to highlight the linkages between groundwater ecosystem services and institutions.

2.1 Exploring groundwater ecosystem services from an integrative perspective

Global concerns with the increased use of groundwater and the corresponding decline of groundwater quality and quantity has necessitated renewed attention towards the issues of groundwater governance (Mukherji and Shah, 2005). In order to understand how and why groundwater governance and management regimes succeed or fail requires high-quality information, both hydrogeological and socio-economic. In this context we view institutional response as an important component of a governance regime (Pahl-Wostl, 2009). The term response is reflecting the activities and behavior of humans as a reaction to system disruptions or alterations. As institutions must constantly deal with changes in Social Ecological Systems institutional response should possess characteristics such as flexibility, openness, transparency, and practicality which in turn enhance the adaptive capacity of governance regimes.

A precondition for successful institutional response incorporates integrative perspectives on groundwater ecosystem services which influence the overall Social Ecological Systems. Integrative institutional perspectives are those which intentionally and actively address ecosystem services and human well-being simultaneously. Doing so, it is necessary to involve actors operating at different levels in order to consider diverse knowledge and expertise. Levels are here related to administrative boundaries: international, national, regional, and local as well as natural hydrological boundaries: supra basin, basin, sub basin.

Integrative groundwater institutions offer considerable advantages. They provide a basis for the effective and sustainable management of groundwater ecosystem services through (adopted from Nanni et al., 2006):

- guidelines for, and limitations to, the exercise of public powers,
- provision for the quantification, planning, allocation and conservation of groundwater resources,
- a system of water pollution control,
- definition of the rights and duties of groundwater users,
- protection of user rights, of the rights of third parties and of the environment,
- requirements for the registration and qualification of well drillers as well as provisions for groundwater monitoring,
- possible administrative interventions in critical situations (aquifer depletion or pollution), and
- provision for cooperative interaction between water administration and water users and facilitating stakeholder participation.

The overall challenge for groundwater management is then, to transform integrative perspectives into institutions that guide wise management practices in resources planning and development (Daily and Matson, 2008).

2.2 Conceptual framework

Institutional response is often induced by certain drivers of change which either have the power to deteriorate social-ecological-systems into undesired states or trigger change towards more adaptive management resulting in new forms of governance systems with the ability to manage dynamic ecosystems (Folke et al., 2005). Thereby, a driver is any natural or human induced factor that causes change in the Social Ecological System and influences the institutional response. Understanding the factors that causes these changes is essential for designing interventions that enhances positive and minimize negative impacts (MA, 2005).

In order to analyze institutional response during periods of change and to determine the effectiveness of institutions on managing groundwater ecosystem services, a framework is required which is able to incorporate institutions and ecosystem services in a holistic manner. We developed such a framework (Figure 1) which highlights the role of institutions governing groundwater ecosystem services and the drivers influencing institutional response. The conceptual foundation of this framework builds upon the Millennium Ecosystem Assessment framework for documenting, analyzing and understanding the effects of environmental change on ecosystems and human well-being (MA, 2005). We adapt this framework as an attempt to explain the effects of institutions on societal and ecological systems. Doing so, the framework combines a reciprocal approach in which humans create institutions and use them when they interact on the one side (Ostrom, 2008) and in which human behavior and interactions are influenced by existing institutions on the other side (Young, 2002).

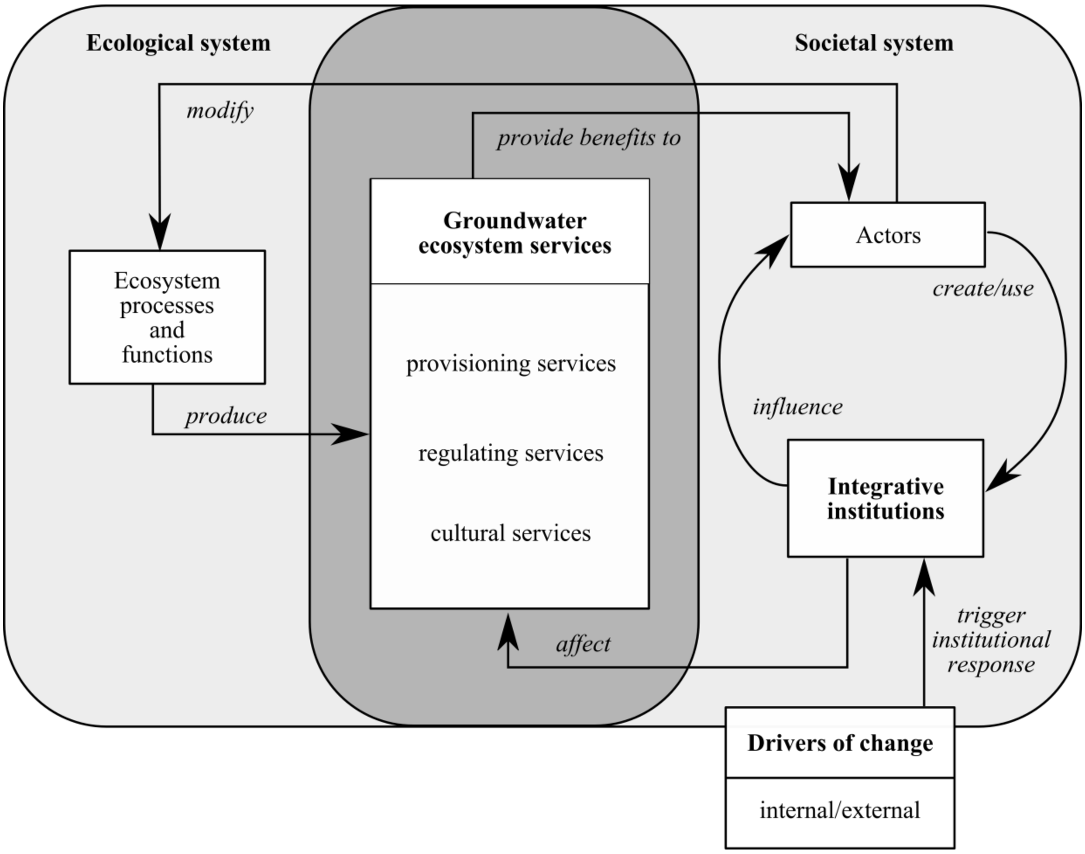

Figure 1*:* Conceptual framework: linking groundwater ecosystem services and the role of institutions nested in a Social Ecological System

This framework explores the institutional response across case studies in two steps: (i) the analysis of internal and external drivers of change triggering institutional response and (ii) the effectiveness and integrative perspectives of institutions on groundwater ecosystem services. The distinction between internal and external drivers of change provides an opportunity to include highly diverse types of drivers crucial to explain the role of responses in describing, understanding, and projecting changes in groundwater resources, ecosystem services and human well-being. The groundwater ecosystem services are categorized according to the Millennium Ecosystem Assessment into four broad categories: provisioning, regulating, supporting, and cultural services. This categorization serves as a functional abstraction from ecological resources to 'used services' that highlight the linkages and dependencies between these services and human well-being (Loring et al., 2008). Groundwater ecosystem services reflect industrial requirements (e.g. agriculture and mining), basic human needs (e.g. water for drinking, cooking and sanitation), regulating functions (e.g. base flow to river and springs, erosion and flood control), and cultural beneficiaries of groundwater (e.g. recreation).

On the one side it is argued that institutions have the power to shape incentives in human exchange and collaboration and contain mechanisms to control people's rights to use the environment. Further, they mediate the link between ecosystem services and the constituents and determinants of human well-being (MA, 2005). Therefore, they link society to nature, and govern social-ecological-systems in a complementary way aspiring long-term objectives (Hanna et al., 1996; Gómez-Baggethun and Kelemen 2008). On the other side, institutional constraints might restrict applicability and effectiveness of adaptive management and Lee (1993) further states that institutional rigidities provide possible barriers to the successful application of an adaptive management approach.

Overall it becomes apparent that institutional design does not provide blueprint approaches to groundwater governance and management. We follow Ostrom et al. (2007) who argue that actors who create and use institutions rather have to be flexible and adaptive by moving beyond panaceas to develop cumulative capacities to diagnose complex problems and potentialities of linked groundwater ecosystem services nested in different contexts.

3. Materials and Methods

The selection of groundwater ecosystem services comprise: provisioning (n=3), regulating (n=5) and cultural services (n=3). This set of groundwater ecosystem services was elaborated based upon literature review on hydrogeological and ecological circumstances of the individual case studies. To verify if our set of groundwater ecosystem services is appropriate to the case study requirements we further discussed this set with case study experts and made changes where necessary. The Annex Table S1 provides a description of the individual groundwater ecosystem services which underline their importance in the individual case studies.

3.1 Management and Transition Framework

As groundwater institutions fall in a domain of different responsibilities including economics, law, public policy, science, and technology we chose an interdisciplinary approach that builds upon the Management and Transition Framework. This framework supports the analysis and standardized representation of complex water management, multi-level governance regimes and transition processes in different case studies towards adaptive management (Pahl-Wostl et al., 2010). The framework is well suited for analyzing adaptation policies and institutions because it inter alia builds upon the concept of adaptive management that has emerged as a response to the complexity of natural resources (Holling, 1978; Pahl-Wostl, 1995; Lee, 1999; Folke et al., 2005). We use the Management and Transition Framework to investigate the role of institutions created during policy and management processes. To organize and structure different elements that influence groundwater governance regimes the Management and Transition Framework incorporates basic structural conditions (e.g. aquifer systems, groundwater ecosystem services, institutions) as well as elements that shape management processes (e.g. actors, action situations, action arenas). The framework was turned into an operational tool through the usage of a relational database in Microsoft Office Access. The database facilitates the storage of large amounts of data and provides the possibility for structured analyses (Knieper et al., 2010). Further, the technical application of the database enables us to establish a chronological presentation of groundwater management processes. Hence, we were able to identify change in important structural basic conditions and alteration of elements shaping groundwater management as a trend over a certain time period.

The analysis was conducted by a set of standardized protocols (=queries) in order to filter and sort required information to answer the research questions. The queries were calculated to analyze the relationships between groundwater ecosystem management, institutions and groundwater ecosystem services.

For a more precise description of the development of the framework, the conceptual foundations and the database approach we refer to Knieper et al. (2010); Pahl-Wostl et al. (2010) and Knüppe and Pahl-Wostl (2011).

3.2 Data collection and analysis

The procedure of data collection was based on an intensive document research (study of legal documents, publications of laws and regulations, research reports and peer reviewed articles) and series of expert interviews during field work in South Africa, Spain and Germany in the years 2009-2011. In each case study the number of interviewees ranged between 18-22 experts. We chose the interviewees based upon their specific knowledge and broad experience in the field of groundwater resources management. The experts reflected various types of expertise: politics and administration, consulting, water supply, forestry, research, and nature conservation.

Together with the interviewees we established a historical representation of groundwater management processes covering the last 20-25 years (e.g. the institutional development or the establishment of a water user association). Management processes are represented as a sequence of Action Situations. Each individual Action Situation maps a structured social interaction context of groundwater policies and management processes. Action Situations are shaped by different actors at different levels and their interaction among each other. According to Ostrom (2005), a primary criterion to constitute an Action Situation is whenever two or more actors are faced with a set of potential actions that jointly produce an outcome. Outcome is here linked to institutional response and measurable effects impacting the state of groundwater ecosystem services (e.g. land use change, composition of water chemistry, groundwater table drop).

Information about actors, institutions and outcomes of Action Situations were entered in the corresponding database which enables us to structure and analyze a huge amount of data in a systematic fashion (Knieper et al., 2010). The database serves as an underlying condition to investigate the three case studies and their system alterations over time. A general challenge is to choose an appropriate time horizon when analyzing institutional response and ecosystem service alterations. As groundwater ecosystem services have different time lags due to deterioration and recovery processes and institutions have different time lags between management planning and implementation we select an analytical time horizon of 20-25 years: Sandveld (1988-2011), Upper Guadiana (1985-2011) and Spree (1990-2011).

The analysis was divided into two general steps. First, we analyzed drivers of institutional responses to groundwater ecosystem management in each case study. In doing so, we created appropriate aggregations of a sequence of Action Situations into meaningful management and policy processes (Annex Table S2). This aggregation was in turn discussed with case study experts and reinforced with additional literature research.
Second, we investigated integrative perspectives and effectiveness of institutions. As an outcome of Action Situations we identified the role of different institutions in groundwater management across the case studies at different periods in time. We reviewed them carefully and studied whether these institutions comprise a diverse set of regulatory provisions and measures towards integrative perspectives on groundwater ecosystem services. We defined integrative perspectives as those that address groundwater ecosystem services and human well-being simultaneously. Finally, we established variables to determine the effectiveness of institutions over time as the degree of implementation (fully, partially, or hardly) and their corresponding effects on environmental and societal systems (Annex Table S3).

4. Case studies
We examined three cases that have experienced substantial changes of their groundwater governance and management regimes in which the awareness and significance of groundwater ecosystem services increased continuously: the Sandveld in South Africa, the Upper Guadiana in Spain and the Spree in Germany (Figure 2).

Figure 2: Geographical location of case studies

In each of these cases, human modifications of the landscape-water system constitute the main cause for deteriorations of groundwater quantity, quality and dependent ecosystems. The degree of usage and protection of groundwater ecosystem services varies across the case studies.

The Sandveld is located at the west coast of the Western Cape Province and is part of the Olifants-Doorn Water Management Area. The Sandveld contains sandy and nutrient poor soils and comprises granular primary aquifers and deeper fractured rock secondary aquifers. The Upper Guadiana is located in the south-eastern part of Spain's Central Plateau and falls into Castilla-La Mancha Autonomous Community. The hydrogeology of the Upper Guadiana is naturally characterized by high interrelations between surface and groundwater bodies resulting in a series of lagoons and wetlands of unique ecological value. Agriculture is the dominant sector in both case studies accounting for more than 90% of groundwater abstraction. Intensive irrigation using groundwater has helped transform largely poor rural regions into important agricultural centers. Determinations of ecological water requirements for the Sandveld and the Upper Guadiana indicate that unsustainable development of groundwater is impacting environmental flows and reducing the availability of many groundwater ecosystem services (Varela-Ortega et al., 2011; Münch and Conrad, 2006).

The Spree is a sub-basin of the River Elbe and flows through the Federal States Saxony, Brandenburg and Berlin. The hydrogeology, soil formation and vegetation of the Spree basin are characterized by a high interrelation between surface and groundwater bodies. Lignite mining constitutes the main human activity connected to groundwater related problems in the Spree. Currently there exists insufficient water availability and quality due to the open pit lignite mining over the last hundred years resulting in an 8km³ deficits in the groundwater balance (Pusch and Hoffmann, 2000). Table 1 provides further information of the study sites.

Table 1: System elements of the case studies

System elements	Attributes	Case studies		
Water system		**Sandveld**	**Upper Guadiana**	**Spree**
	Basin area (km²)	4.590	16.000	10.100
	Precipitation (mm/a)	200	415	530
	Evapotranspiration(mm/a)	1.600	1.000	610
	Climate-Moisture Index	Semi-arid	Semi-arid	Sub-humid
Societal system		**Western Cape Province**	**Castilla La Mancha**	**Brandenburg**
	Population density (inhabitants/km²)	< 20	24,85	29,5
	Economic sector	Agriculture	Agriculture	Lignite mining, fishery, tourism
Ecological system		***Verlorenvlei* RAMSAR Site**	***Las Tablas de Daimiel National Park* RAMSAR Site**	***Spreewald* UNESCO Biosphere Reserve**
	Water availability	Low	Low	Medium
	Degree of human influence	High	High	High
Natural hazards		**Droughts**	**Droughts**	**Droughts, floods**
	Frequency-intensity distribution	Annual – during summer; the drought extent depends on rainfall during winter	Irregular – increasing tendency during summer	Regular droughts (summer) and irregular floods (mainly winter)

These cases have each developed a body of knowledge that we use in our analysis. This research builds upon our previous research experience in these regions and benefits from our existing contacts with case study experts.

5. Results and discussion

First we describe the drivers of institutional responses to groundwater ecosystem management in each case study, and second we analyze how institutions operate to integrate social and ecological perspectives on groundwater ecosystem services as well as produce effective action.

Institutional responses within the individual case studies are triggered by a diverse set of drivers of change (Table 2). In the Sandveld and the Upper Guadiana the majority of response is induced by ecological drivers and international or national legislative requirements. The Spree, however, provides a relatively even distribution of drivers of change.

Table 2: Types of drivers of change and their occurrence across the case studies

Driver type	Sandveld	Upper Guadiana	Spree
Ecological	3	4	2
Legislative requirements	1	4	2
Economic	1	1	2
Political regime shift	1	-	1
Social	1	1	-
Cultural	-	-	1
Technological development	1	-	-

The consequences of these drivers in producing effective and integrative institutions varied much more than the different driver types, with the Spree doing the best and the Upper Guadiana the worst (Table 3). The effectiveness of institutions is sub-divided into environmental and societal effects.

Below we outline in more detail for each case study how drivers of institutional response generated institutional change over time.

Table 3: Effectiveness and integrative perspectives of formal and informal institutions

	Effectiveness of institutions	Integrative perspectives	Environmental effects	Societal effects
Sandveld	Medium	High	• Expansion of protected areas • Water savings • Sustainable farming practices	• Water User Association • Industry engagement • Education/awareness rising • Public participation
Upper Guadiana	Low	Medium	• Little water savings • Reforestation	• Groundwater User Associations • Compensation payments • Lack of cooperation and communication • Illegal water abstraction
Spree	High	High	• Water protection zones • Expansion of protected areas • Improvement of the overall water balance	• Water pricing system • Education/awareness rising • Public participation • Compensation payments, purchase of land

5.1 Analyzing institutional response in the Sandveld

The case is dominated by ecological drivers of change (Table 2) triggered by the over-abstraction of groundwater for irrigation purposes and the enduring clearing of natural vegetation for potato production. Since the end of the Apartheid era in 1994 South Africa's water legislation has undergone significant institutional changes including a shift of social and ecological perspectives on groundwater. Institutional response has taken place at different levels of management action: national, regional, basin and sub-basin level. This situation induced massive changes of administrative responsibilities and innovative regulatory instruments for water assessment, planning and management, economic instruments to influence water use pattern, as well as cooperative measurements to enhance participation (Annex Table S2). Together, economic and ecological drivers triggered a basic rethinking of what groundwater use and protection means. This rethinking led the potato industry, conservation sector, farmers, and local municipalities of the Sandveld to make a major attempt to integrate and mainstream ecological thinking into the agriculture sector (Annex Table S2, A AS9-15). As an outcome of institutional response we identified both formal regulatory mechanisms and informal guidelines for the Sandveld farmers taking into account provisioning, regulating and cultural ecosystem services. Recently, noncompliance to national legislative requirements (National Environmental Management Act of 1998) has impaired the implementation of the biodiversity favoring farming practices which are legally not recognized. As a response to this dilemma a task team of state and non-state actors was created and developed a law enforcement strategy (Annex Table S2, A AS16).

The effectiveness of institutions is rated as medium whereas integrative perspectives on groundwater ecosystem services are identified as high in the Sandveld (Table 3). Most important institutions managing groundwater in an integrative manner include a diverse set of regulatory provisions and measures (e.g. the registration of water abstraction, hydrogeological mapping) (Annex Table S3). We found that formal institutions established at national level (National Water Act, National Groundwater Strategy) hardly provide any measurable effects while informal institutions constituted at lower levels indicate positive effects on the management of groundwater ecosystem services.

Societal effects incorporate the establishment of a local Water User Association and a substantial increase of industrial engagement in natural resources management such as the establishment of the Greater Cederberg Biodiversity Corridor and the development of Biodiversity Best Practices for Potato Production. In this context we identified environmental effects including the expansion of protected areas and application of sustainable farming practices. These biodiversity favoring farming practices could be more effective if the problem of noncompliance get solved in the near future. This example of the Sandveld indicates the close conjunction between societal and environmental institutional features.

5.2 Analyzing institutional response in the Upper Guadiana

The case is dominated by ecological drivers of change and a set of legislative requirements (Table 2). The former was identified as the general driving force as the ecological consequences of intensive groundwater use for irrigation over the last 40 years has produced substantial of institutional response. This response incorporates international and national agriculture and water reforms to solve the unsustainable usage of groundwater and the enduring degradation of ecosystem services. Many of these responses were to a great extent determined by strict quota systems or bans on drilling new wells while others include compensation payments for farmers or technical solutions such as water transfer schemes (Annex Table S2, B AS1-6).

The European Water Framework Directive has produced major changes and a basic rethinking in water management. Similar to all European member states, Spain adopted the Water Framework Directive in the year 2000 to promote the 'good ecological status' of all water bodies until 2015. The Directive embraces a broad mandate of innovative institutional responses to incorporate economic and ecological considerations: water pricing, ecological objectives, political processes, public participation and new approaches to water planning (Annex Table S2, B AS7). The Water Framework Directive and the National Hydrological Plan of Spain triggered the development of the Special Plan for the Upper Guadiana. The elaboration of this plan took more than 8 years and was at the beginning opposed by the majority of actors in the Upper Guadiana. They claimed that the content of the plan focused mostly on the water requirements of large commercial farmers rather than considering the protection of aquifers and wetlands (Knüppe and Pahl-Wostl, 2011). Today, the plan is considered as a groundbreaking institutional response creating large-scale efforts to restore the complete Social Ecological System of the Upper Guadiana (Annex Table S2, B AS8-13).

The effectiveness of institutions is rated as low whereas integrative perspectives on groundwater ecosystem services are identified as medium in the Upper Guadiana (Table 3). Central institutions managing groundwater

ecosystem services include exclusively formal regulatory provisions and measures such as the Spanish Water Act, the European Agro-Environmental Program, the Water Framework Directive, the European Groundwater Daughter Directive, and the National Hydrological Plan (Annex Table S3). The majority of institutions is hardly implemented in the Upper Guadiana and has therefore almost none positive environmental or societal effects on groundwater management. Both the Water Framework Directive and the Groundwater Daughter Directive focus on water quantity standards and less on groundwater dependent ecosystems and the services they provide. While the implementation of the Water Framework Directive has started in the Upper Guadiana the Groundwater Daughter Directive is hardly implemented.
Societal effects include beside the establishment of Groundwater User Associations the payments for compensation measures. Even though institutional response has led to some short term ecological improvements (Annex Table S2, B AS2-7) overall ecological challenges persist. In addition, some institutions and the way of implementation have produced negative societal effects such as the illegal development of water abstractions and enduring social conflicts between the water administration and water users of the Upper Guadiana. In general, the only two environmental effects we identified comprise a small amount of water savings and reforestation of land.

5.3 Analyzing institutional response in the Spree

Groundwater management in the Spree is being transformed by a wide range of drivers (Table 2). Along with ecological and economic drivers, legislative requirements constitute important drivers of change impacting groundwater management in the Spree. The unification of Germany and parallel economic drivers had enormous impacts on the institutional response such as the liberalization of water markets and the establishment of international standards for water quality and quantity (Annex Table S2, C AS1-2). At the same time ecological conditions were recognized as a requirement to be improved with high priority. As a corresponding response the Federal Republic of Germany set out areas of great importance for nature conservation such as the UNESCO Biosphere Reserve Spreewald in 1990. In this context, ecological and cultural drivers of change triggered different responses to protect the ecological (e.g. wetlands) and the cultural heritage of the Spreewald (e.g. Slavic tribes of the Sorbs). As a direct response to the Biosphere Reserve the Riparian Land Project Spreewald was established. This large scale conservation project of the German Federal State was induced and carried out by local agencies and stakeholders of the Spreewald aiming to safeguard the hydrological flows and to maintain the flora and fauna of the Spreewald (Annex Table S2, C AS4-7). The institutional response incorporates inter alia compensation payments, land purchasing, environmental management plans, and conservation measures to protect different types of groundwater ecosystem services. Like Spain, Germany adopted the Water Framework Directive in the year 2000. Institutional response according to this international legislative requirement can be found in the implementation of measures developed within the Riparian Land Project Spreewald in order to ensure the ‘good ecological status’ of all water bodies until 2015.
As the lignite mining sector located in the upper parts of the River Spree is responsible for hydrogeological modifications including both water quality and quantity degradations institutional response was and still is triggered by international and national legislative requirements (e.g. environmental assessment analysis and development of compensation measures). The mining sector is strongly influenced by economic drivers.

The effectiveness of institutions and integrative perspectives on groundwater ecosystem services are rated as high in the Spree (Table 3). Important institutions to manage groundwater incorporate regulatory provisions and measures developed at international, national and local levels. These institutions set incentives for stakeholders to accept and support innovative approaches to protect groundwater ecosystem services. The Federal Water Act and the Federal Nature Conservation Act of Brandenburg are determined as fully implemented while the Water Framework Directive and the Groundwater Daughter Directive have hardly any environmental effects (Annex Table S3). At sub-basin level the Riparian Land Project Spreewald integrates social and ecological perspectives on groundwater ecosystem management and compassed beside participation processes and awareness rising of ecosystem services concrete measures such as water pricing and compensation payments. The environmental effects incorporate the establishment of water protection zones, expansion of protected areas and a general improvement of the landscape-water system in certain parts of the River Spree. Improvements of both water quality and quantity can be further observed in some parts of the River Spree and the Spreewald. A high degree of ecological improvement is still required in the upper parts of the River Spree.

5.4 Lessons learnt: discussion of case study insights

Despite differences in terms of responsible authorities, institutions and legal requirements, groundwater governance regimes in each of our case studies were increasingly aware of the need to steer their societies towards sustainable management of groundwater for current and future generations. However, our results demonstrate that well-crafted regulatory frameworks are not effective if not implemented in practice (e.g. Groundwater Daughter Directive, South Africa's National Water Act).

The cases reveal that institutional response is primarily embedded in long-term management processes in which surprises or crisis stimulate reorganization that in turn can provide opportunities for new ways of managing natural resources. All case studies illustrate that institutional response is caused by multiple, interacting drivers of change and the effectiveness of implementation depends on different circumstances of Social Ecological Systems. Political and economic shifts as well as legislative requirements open windows of opportunity which allow for new approaches of natural resources management at different levels on the one side and create a variety of complex challenges including altered resource use patterns, new actor constellations of land users and land owners, and modification of the water price on the other side. Ecological drivers are dominant in all case studies. Ecological changes triggered fundamental rethinking of the role of groundwater ecosystem services in formal and informal institutions. In particular, the case studies characterized by intensive agriculture the importance of protecting groundwater ecosystem services increased. In contrast, social and cultural drivers as well as technical development played a minor role generating institutional response across the cases.

We found that the effectiveness of institutions focusing on a single instrument is inadequate to implement an integrative response; rather institutions must incorporate multiple regulatory provisions and measures to support their effective implementation.

There are often no clear linkages between ecological drivers and the institutional response in order to meet environmental challenges. This disconnect becomes in particular evident in the Upper Guadiana where the majority of institutional responses were triggered by ecological drivers but their effectiveness is low and the ecological state of groundwater ecosystem services remains poor. However, legislative requirements have a stronger capacity to push institutions towards integrative perspectives than other drivers. Although, the institutional response to solve environmental challenges grew continuously, the effectiveness and implementation of institutions require longer time frames before impacts can be realized or a broad constituency of support can be established.

Below we summarize important lessons learnt from the management of groundwater ecosystem services across the case studies. Table 4 shows that multiple groundwater ecosystem services occur simultaneously which in turn produces trade-offs. If groundwater management and institutions focuses on the delivery of a single service rather than take into account their interrelations, the magnitude and mix of services might result in irrecoverable change.

Table 4: Groundwater ecosystem services across case studies (we do not include supporting services because these services are defined as '*those that are necessary for the production of all other ecosystem services*' (MA, 2005))

Ecosystem service types	Groundwater ecosystem services	Sandveld	Upper Guadiana	Spree
Provisioning *'products obtained from ecosystems'*	• Irrigation	X	X	-
	• Domestic supply	X	X	X
	• Power-plants	-	-	X
Regulating *'benefits obtained from the regulation of ecosystem processes'*	• Purification/waste treatment	-	-	X
	• Drought buffer	X	X	X
	• Erosion/flood control	-	-	X
	• Base flow	X	X	X
	• Flora/fauna habitat	X	X	X

Cultural *'non-material benefits that people obtain from ecosystems'*	• Recreation/tourism	X	X	X
	• Aesthetic beauty	X	X	X
	• Education, research	X	X	X

Provisioning services: Institutions attach great importance to provisioning services because they play a crucial role by supporting human well-being including social standards and economic development. Provisioning groundwater ecosystem services (e.g. irrigation, mining activities, drinking and sanitation supply) are regulated by stricter institutions and mechanism (i.e. primarily formal laws) controlling their use and allocation (registration and licensing of water abstraction, pricing systems) than regulating and cultural services. Approaches to provisioning services have shifted over the last two decades from a focus on single ecosystem services towards integrative perspectives that incorporate multiple ecosystem services. Institutional response aims to better manage trade-offs between provisioning and regulating and cultural ecosystems services that is reflected in diverse ecological problems and social conflicts across the cases.

Lessons learnt. The Sandveld and Upper Guadiana demonstrate how institutional response incorporates both the water requirements for irrigation purposes and water requirements to sustain environmental flows and ecosystem services (e.g. Biodiversity Best Practices for Potato Production in the Sandveld, Special Plan for the Upper Guadiana). Both case studies developed instruments to mainstream the protection of groundwater ecosystem services into the agriculture sector. Albeit it is important to note that the effectiveness varies between the two cases.

Regulating services: In general, regulating services are unrecognized and actors are not aware of these services until a service declines or is lost and impacts human well-being. For example the intensive extraction of groundwater for agriculture or mining activities negatively influences the groundwater base-flow to rivers, streams and wetlands that in turn supports groundwater specific flora and fauna habitats. In some cases specific regulating services improved due to institutional responses. In these cases local communities and stakeholders were included in developing and implementing new institutions to protect regulating services.

Lessons learnt. Bottom-up responses in the Sandveld incorporated multi-stakeholder processes during the development of the Greater Cederberg Biodiversity Corridor and the establishment of Biodiversity Best Practices for Potato Production. Within a multi-stakeholder process a conservation and development plan was developed including different regulatory provisioning and measures supporting inter alia base flow and flora and fauna habitats. This response includes a high acceptance of new approaches to protect regulating services without negatively impacting provisioning services and consequently the livelihoods of people in the Sandveld. The Riparian Land Project Spreewald is a groundbreaking institutional response because it acknowledged different regulating groundwater ecosystem services (Table 3).

Cultural services: Cultural services play a crucial role across the case studies (Table 4). All cases include international protected ecosystems (Sandveld: Verlorenvlei RAMSAR Site, Upper Guadiana: RAMSAR Site Las Tablas de Daimiel National Park, Spree: Spreewald UNESCO Biosphere Reserve) that are important for recreation and tourism, as well as education and research. Unfortunately, many cultural services are not adequately or explicitly captured in institutional response - especially in areas making intensive use of provisioning services. Albeit groundwater constitutes an essential component of everyday life and is integrated throughout different cultural services in the case studies, institutional response has only slowly begun to incorporate non-material benefits that people obtain from groundwater ecosystems.

Lessons learnt. Actors can be willing to support and maintain cultural services when their well-being clearly depends on those services. This is the case in South Africa, where the protection and maintenance of cultural services are acknowledged in formal institutions of South Africa (e.g. National Water Act, National Water Resource Strategy) and informal institutions developed in the Sandveld (e.g. Greater Cederberg Biodiversity Corridor). This is true to a lesser extent in the Spree in which cultural services are solely dealt with via informal institutions (e.g. Riparian Land Project Spreewald).

6. Conclusions

The institutional responses of groundwater governance and the management of ecosystem services reveal general features across our case studies. First, institutional responses tend not to be fully integrated, and second that well-crafted institutions are not sufficient to produce socially, ecologically or economically satisfactory results. Albeit the Sandveld, Upper Guadiana and Spree have developed considerable water institutions over the past 20-25 years, specific ecosystem services are hardly mentioned and the actual protection of groundwater ecosystem services has been slow and inconsistent. In particular, we show that groundwater governance tends to favor the management of provisioning ecosystem services over regulating or cultural services. While provisioning services may be more valuable than other services, we suspect that the public good nature of regulating and cultural services leads to underinvestment in them. These results are broadly similar to many assessments of ecosystem services (MA, 2005; Raudsepp- Hearne et al., 2010).

Groundwater institutions seldom acknowledge the spatial and temporal dimensions and linkages of multiple ecosystem services nor the functional diversity, key structuring processes, and resilience in ecosystems. Thereby it is nothing new that social and ecological systems and their processes have spatial and temporal dimensions in which ecosystem services occur. The main challenge for natural resources managers is, however, to match the scale (temporal, spatial, and functional) of institutions to the ecosystem being managed. Our three examples identify the difficulties to capture these high demands for effective and integrative institutional response. Folke et al. (2007) highlight that progress has been made on the 'match problem', although most research on sustainable resources development and human futures still treats social and ecological systems as separated entities.
In this context, there persist many open social-ecological questions that require trans-disciplinary research that draws upon both social and natural sciences to understand how human actions affect the state of ecosystems, and the provisioning of ecosystem services, and the value of those services (Daily and Matson, 2008). While there remain a variety of tools of managing uncertainties and making decisions in unclear situations (Holling, 1978; Walters, 1986; Scholz, 2011), there is a need to operationalize these tools into real world ecosystem services governance.

Our research provides a basis for future empirical work on how institutions affect and govern ecosystems and their services and consequently impact human well-being in both developed and developing countries. By applying our novel conceptual and analytical approach to different cases around the world it extends the knowledge and experience derived from different techniques and management approaches governing groundwater or other natural resources. In doing so, cross-country studies have considerable value in sharpening the overall understanding of the mechanism of institutional change and their ultimate impact on social and ecological system elements. This in turn enables researchers to establish a credible basis for deriving both generic and case study specific strategies in order to provide adequate policy advice. Following Boulton (2009), scientists must continue to report their findings beyond just the scientific literature and be proactive in discussing the implications of their work with water managers and policy makers. It is further crucial to acknowledge that the science-policy debate is not a one-way flow. Therefore, a dialogue of successive refinement of questions and approaches remains important to better understand the requirements for integrative institutions governing groundwater ecosystem services: who determines which ecosystem services should be prioritized for groundwater protection and which components of these services should be valued? Finally, it is crucial to ask how groundwater ecosystems and their services change over time and what are appropriate time horizons to analyze impacts on Social Ecological Systems? We hope addressing these questions will contribute to new insights of integrative global change science.

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Annex

Table S1 Groundwater ecosystem services

Groundwater ecosystem service	MA category	Explanation
Irrigation	Provisioning	Groundwater is a storage and retention for irrigated agriculture. The scale and rate of groundwater use for irrigation increased substantially due to the massive expansion in pumping capacity.
Domestic supply	Provisioning	Groundwater is used for drinking and cooking as well as for sanitation and washing requirements as a basic human need.
Power-plants	Provisioning	Groundwater is used for lignite power-plants as a method of heat removal from components and industrial equipment (in the context of coal mining).
Purification/ waste treatment	Regulating	The biological component of the groundwater environment provides an important service in the form of water purification and waste treatment through microbial degradation of organic compounds and potential human pathogens.
Drought buffer	Regulating	Groundwater acts as the primary buffer against the impact of climate variability and spatial variability in drought. The buffer potential depends of the soil and rock types of the aquifer.
Erosion/flood control	Regulating	Groundwater aids in the control of erosion and floods by absorbing runoff. In addition, groundwater indirectly regulates soil erosion by providing water to vegetation cover.
Base flow	Regulating	Base flow derived from groundwater discharge is a fundamental service in many areas where springs and the dry-season flow depend heavily on groundwater. Base flow controls factors governing the extent of wetlands and surface vegetation types.
Flora/fauna habitat (biodiversity)	Regulating	There are numerous flora and fauna habitats that depend partly or totally on groundwater. Biodiversity issues generally relate to the regions where aquifers discharge through rivers, lakes or swamps. These areas form critical wildlife habitats and serve as sources of food, fuel and timber.
Recreation/ tourism	Cultural	Local communities and visitors often choose where to spend their leisure time based in part on the characteristics of the natural or cultivated landscapes in a particular area.
Aesthetic beauty	Cultural	Many people find beauty or aesthetic value in various aspects of groundwater dependent ecosystems, as reflected in the support for parks, scenic drives, and the selection of housing locations.
Education/research	Cultural	Groundwater, dependent ecosystems and the services they provide offer plenty of opportunities for education and research.

Table S2 Overview of Action Situations influencing institutional response in the Sandveld, the Upper Guadiana and the Spree case study

SANDVELD, SOUTH AFRICA						
No.	**Action Situations**	**Spatial level**	**Drivers of change**	**Institutional response**	**Institutional focus on groundwater ecosystem services**	**Millennium Ecosystem Assessment category**
A AS1	Access to electricity	Sub-basin	Technological development	Expansion of irrigated land and the potato market	Irrigation	Provisioning
A AS2	Enactment of National Water Act (NWA)	National	Political regime shift, social and ecological drivers	Shift of water legislation: - National Water Resource Strategy - Registration/licensing of water abstraction - Ecological reserve calculation - Decentralization of water management	Irrigation Domestic supply Purification/ waste treatment Drought buffer Base flow Flora/fauna habitat Recreation/tourism	Provisioning Provisioning Regulating Regulating Regulating Regulating Cultural
A AS3	Exploration of the Sandveld area	Sub-basin				
A AS4	IWRM phase I	Basin				
A AS5	Establishment of the Catchment Management Agency (CMA) Proposal	Basin				
A AS6	Ministerial Visit to the Sandveld	Sub-basin				
A AS7	IWRM phase II	Basin				
A AS8	Establishment of the Sandveld Water User Association (WUA)	Sub-basin				
A AS9	Announcement of the C.A.P.E. Strategy	National	Ecological drivers	Mainstreaming biodiversity and conservation into the production sector - Biodiversity Act (2004) - Protected Areas Act (2003) - National Environmental Management Act (1998)	Flora/fauna habitat Recreation/tourism Aesthetic beauty	Regulating Cultural Cultural
A AS10	Establishment of GCBC	Regional				
A AS11	Biodiversity Stewardship Program	Sub-basin				
A AS12	Implement Biodiversity and Business project	Sub-basin				
A AS13	Elaboration of 'Biodiversity Best Practices for Potato Production (BBP)'	Sub-basin	Economic and ecological drivers	Informal (voluntary) program for farmers - Registration of water abstractions - Restrictions of land clearing - Environmental management plans	Irrigation Base-flow Flora/fauna habitat	Provisioning Regulating Regulating
A AS14	Implementation of BBP	Sub-basin				
A AS15	Evaluation of BBP	Sub-basin				
A AS16	Development of a Joint Forcement Strategy	Regional	Legislative requirements	Inter-departmental task team of state and non-state - Remote sensing of suspected farm properties (illegal developments)	Irrigation	Provisioning
UPPER GUADIANA, SPAIN						
No.	**Action Situations**	**Spatial level**	**Drivers of change**	**Institutional response**	**Institutional focus on groundwater ecosystem services**	**Millennium Ecosystem Assessment category**

B AS1	Declaration of over exploitation of Western Mancha aquifer	Sub-basin	Ecological drivers	Aquifer restructuring plan: - Drilling ban - Formation of Water User Associations - Ban on deepen existing wells - Declaration of strict water quotas	Irrigation Base-flow	Provisioning Regulating
B AS2	Implementation of Water Abstraction Plans (WAP)	Sub-basin	Legislative requirements, social, economic and ecological drivers	International and national reforms: - Income compensation payments for farmers - Water quotas	Irrigation	Provisioning
B AS3	Implementation of Agro-Environmental Program (AEP)	Sub-basin				
B AS4	Modulation of AEP	National				
B AS5	Approval of the National Hydrological Plan (NHP)	National	Legislative requirements, ecological drivers	Water transfer/regulation schemes from river catchments that have (so-called) water "in excess" to catchments with a (so-called) "water deficit"	Base-flow Flora/fauna habitat	Regulating Regulating
B AS6	Tajo-Guadiana water transfer	National				
B AS7	Adoption of the Water Framework Directive (WFD)	National	Legislative requirements	Mandates of the WFD includes: water pricing, ecological objectives, political processes, public participation and new approaches to water planning.	Irrigation Domestic supply Drought buffer Flora/fauna habitat	Provisioning Provisioning Regulating Regulating
B AS8	Elaboration of Special Plan for the Upper Guadiana basin (SPUGB) proposal	Sub-basin	Legislative requirements, social and ecological drivers	Content of the SPUGB: - Purchasing water rights - Socio-economic restructuring plan - Reforestation plan - Extensive rainfed farming	Irrigation Drought buffer Base-flow Flora/fauna habitat	Provisioning Regulating Regulating Regulating
B AS9	Presentation of SPUG to Guadiana River Basin Council	Sub-basin				
B AS10	Public Information process on SPUG	Sub-basin				
B AS11	Elaboration of new guidelines/draft of SPUG	Sub-basin				
B AS12	Submission of SPUG for public review	Sub-basin				
B AS13	Formal approval of SPUG	National				
SPREE, GERMANY						
No.	**Action Situations**	**Spatial level**	**Drivers of change**	**Institutional response**	**Institutional focus on groundwater ecosystem services**	**Millennium Ecosystem Assessment category**
C AS1	Reunification of Germany	**National**	Political regime shift, economic drivers	Liberalization of the water market, new water charges, international standards for water quality and quantity	Power-plants	Provisioning
C AS2	Abrupt closure of open pit lignite mines	**Regional**				

C AS3	Establishment National Park Program	**National**	Ecological drivers	Guidelines for protected areas of international importance, environmental contracting	Flora/fauna habitat Recreation/tourism Aesthetic beauty	Regulating Cultural Cultural
C AS4	Release of first project conception of Riparian Land Project Spreewald	**Sub-basin**	Ecological and cultural drivers	Conservation and development plan including: compensation payments, land purchasing, environmental management plans, diverse conservation measures	Erosion/flood control Drought buffer Base-flow Flora/fauna habitat Recreation/tourism Aesthetic beauty	Regulating Regulating Regulating Regulating Cultural Cultural
C AS5	Manifold revisions and modifications of the project conception	**Sub-basin**				
C AS6	Official approval of Riparian Land Project Spreewald	**Sub-basin**				
C AS7	Development and implementation of the conservation and development plan	**Sub-basin**				
C AS8	Adoption of the Water Framework Directive (WFD)	**National**	Legislative requirements	Mandates of the WFD includes: water pricing, ecological objectives, political processes, public participation and new approaches to water planning.	Irrigation Domestic supply Drought buffer Flora/fauna habitat	Provisioning Provisioning Regulating Regulating
C AS9	Implementation of (mining) compensation measures	**Basin**	Legislative requirements, economic drivers	Environmental assessment analysis (international standards), compensation measures	Power-plants	Provisioning
C AS10	Planning about exploitation of new lignite mining areas	**Regional**				

Table S3 Institutions, their regulatory provisions and measures, and effectiveness on Social Ecological Systems

Institutions	Regulatory provisions and measures	Implementation	Environmental effects	Societal effects
SANDVELD, SOUTH AFRICA				
National Water Act (1998)	- Registration/licensing of water abstraction - Ecological Reserve - Decentralization of water management	Partly	- (Temporary) reserve calculations	- Establishment of Northern Sandveld Water User Association - Still no Catchment Management Agencies
National Groundwater Strategy (2010)	- Hydrogeological mapping - National Groundwater Database - Groundwater Reserve	Hardly	No measureable effects by now	
Greater Cederberg Biodiversity Corridor	- Landowner database - Area wide planning	Partly	- Expansion of protected areas - Reestablishment of flora and fauna habitats	- Industry engagement and local economic development - Education and awareness rising
Biodiversity Best Practices for Potato Production	- Environmental Management Plan o Guidelines for soil, irrigation, fertilizer, and integrated pest management	Partly	- Efficient irrigation techniques - Water savings - Decrease of fertilizers and pesticides	- Industry engagement - Multi-stakeholder process - Many farmers join the Program (voluntarily)

	○ GIS reference maps ○ Financial planning - Accreditation of good agricultural practice		- Buffer zones - Clearing of alien invasive plants	
UPPER GUADIANA, SPAIN				
Spanish Water Act (19985, amended in 1999 and 2003)	- Registration of groundwater abstractions - Official declaration of aquifer overexploitation ○ Water Management Plans and yearly pumping restrictions	Partly	- Not very successful in environmental issues - Mancha aquifer was declared overexploited	- Private and public rights co-exist in the same aquifer - Establishment of Groundwater User Associations - Legal reaffirmation of public participation - Lack of educational and informational efforts by the Bain Agencies
EU Agro-Environmental Program 1	- Voluntary water quatos and income compensation payments independent of farm size	Fully	- Lower water consumption - Modern irrigation techniques - Increase of low-water demanding crops - Recovery of the aquifer - Partial restoration of wetlands	- Large adoption rate by farmers - Sufficient compensation payments - Farm income gain - Social stability - Low cost-effectiveness
EU Agro-Environmental Program 2	- Voluntary water quatos and income compensation payments according to farm size (based on the pumping restrictions of the Spanish Water Abstraction Plans)	Hardly	- No recovery of the aquifer due to low implementation of the program - Illegal water abstraction	- Low adoption by farmers - Social unrest - Compensation payments are not sufficient - Farm income loss
EU Water Framework Directive (2000)	Achieve good qualitative and quantitative status of all water bodies by 2015. - River Basin Management Plans - Water pricing instruments	Partly, implementation until 2015	- Amelioration of the ecological conditions of watercourses - Lower water use in some areas	- Transparency and public participation - Accountability and cost effectiveness assessment of policy measures
EU Groundwater Daughter Directive (2006)	- Measures of water quality standards (e.g. nitrates, pesticides)	Hardly	No measureable effects by now	
National Hydrological Plan	Special Plan for the Upper Guadiana Basin: - Purchasing water rights - Socio-economic restructuring plan - Reforestation plan - Extensive rainfed farming	Hardly	- Reforestation of land	- High enforcement costs - Generation of rural employment - (Partly) purchase of water rights - Illegal water abstraction - Funding is not completely materialized
SPREE, GERMANY				
Federal Water Act of Brandenburg (2004)	- Water protection zoning - Sewage disposal plans - Pure retaining orders - Water management/framework plans	Fully	- Water protection zones increase groundwater quality and quantity	- Water pricing systems - Public participation, access to information - Decentralization of different task and responsibilities to various state and non-

				state agencies
Federal Nature Conservation Act of Brandenburg (2004)	- Network of interlinked biotopes o Biosphere Reserve Spreewald - Impact regulations; FFH impact assessment - Landscape programs and master plans	Fully	- Expansion of protected areas - Resettlement of rare species	- Compensatory measures for utilization restrictions (agriculture, forestry and fishing)
EU Water Framework Directive (2000)	Achieve good qualitative and quantitative status of all water bodies by 2015. - River Basin Management Plans - Water pricing instruments - Masterplan Spree	Partly, implementation until 2015	No measureable effects by now	- Transparency and public participation - Accountability and cost effectiveness assessment of policy measures
EU Groundwater Daughter Directive (2006)	(see UGB)	Hardly	No measureable effects by now	
Riparian Land Project Spreewald (2005-13)	Conservation and development plan - Development of a backwater system - Deconstruction of dehydration systems, protection and creation of flood plains. - Reintroduction of periodic flooding	Partly, implementation until 2013	- Increase of habitat creation and restoration - Increase of flora/fauna - Improvement of surface-groundwater connections	- Multi-stakeholder process - Purchase of land - Compensation payments