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How the Social-Ecological Systems Concept Can Guide Transdisciplinary Research and Implementation: Addressing Water Challenges in Central Northern Namibia

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Received: 6 February 2017; Accepted: 16 June 2017; Published: 26 June 2017

Abstract: Research aimed at contributing to the further development of integrated water resources management needs to tackle complex challenges at the interface of nature and society. A case study in the Cuvelai-Etosha Basin in Namibia has shown how semi-arid conditions coinciding with high population density and urbanisation present a risk to people's livelihoods and ecosystem health. In order to increase water security and promote sustainable water management, there is a requirement for problem-oriented research approaches combined with a new way of thinking about water in order to generate evidence-based, adapted solutions. Transdisciplinary research in particular addresses this issue by focusing on the problems that arise when society interacts with nature. This article presents the implementation of a transdisciplinary research approach in the above-mentioned case study. The concept of social-ecological systems (SES) plays a key role in operationalising the transdisciplinary research process. Application of the SES concept helps to outline the problem by defining the epistemic object, as well as structure the research process itself in terms of formulating research questions and developing the research design. It is argued here that the SES concept is not merely useful, but also necessary for guiding transdisciplinary sustainability research and implementation. The study from Namibia clearly demonstrates that the introduction of technological innovations such as rainwater and floodwater harvesting plants requires a social-ecological perspective. In particular this means considering questions around knowledge, practices and institutions related to water resources management and includes various societal innovations alongside technologies on the agenda.

Keywords: Cuvelai-Etosha Basin; savannah ecosystems; ecosystem services; integrated water resources management; rainwater and floodwater harvesting; social-ecological systems; transdisciplinary research

1. Introduction

Many semi-arid regions in the world are facing problems such as water scarcity, infertile land, the impacts of climate change, population growth, urbanisation processes and inadequate water supply and sanitation [1–4]. Water-related problems are manifold and complex in how they are manifested in different sectors and at different levels in society [5]. In order to improve water security and address inequality and injustice, there needs to be improved understanding of the key societal and ecological elements and drivers of these complex systems as well as their interrelations, and their (self-regulatory) capacity needs to be strengthened [5]. It is therefore a challenge to develop evidence-based solutions that increase the resilience of these systems [6] and pave the way for broader replication in future in the region and beyond.

Fundamental research projects and straightforward development cooperation are pushed to their limits in the face of these challenges. The answer is to shift the focus towards linked 'research and development' approaches, often referred to as 'research for development' [7]. This is particularly the case if potential solutions and their implementation are linked to innovations such as specific technological developments and new forms of management strategies and practices. Suitable approaches need to fulfil specific requirements such as the integration of different disciplines and the linking of science with society in order to allow an analysis of the complex interplay between social and ecological processes and structures and offer feasible solutions for sustainable resource management [8,9].

Transdisciplinary research is able to meet this challenge. In particular it addresses problems with societal relevance at the science-practice interface and therefore necessitates the involvement of stakeholders and relevant scientific disciplines [8,10]. The concept of social-ecological systems (SES) is very well suited to transdisciplinary research for sustainability because these systems can be understood as concrete epistemic objects in the real world of spatio-temporal phenomena [11]. These phenomena are viewed and conceptualised differently by various authors, e.g., as 'human-nature relations' by Glaser [11,12] or as 'societal relations to nature' by Becker [13] and Hummel et al. [14]. SES support the structuring of real-world problems on a clear conceptual foundation, thereby taking into account the aforementioned interplay between society and nature which is a typical issue that can be addressed by transdisciplinary approaches. When applied to case studies, SES are usually understood to be provisioning systems, with "provisioning" being used in a wide sense to include any material or even symbolic benefit that society can draw from natural resources [14].

In this paper, the implementation of rainwater and floodwater harvesting (RFWH) in the Cuvelai-Etosha Basin (CEB) in central northern Namibia served as a case study for applying the SES concept in a transdisciplinary research setting. The case study is part of a larger transdisciplinary research and development project designed to last for around ten years. The CEB is a typical example of semi-arid conditions in which there is limited availability and inefficient use of water [9,15]. Thus, the growing population is exposed to physical water scarcity [15] which is aggravated by inadequate socio-economic capacities and challenged by climate change [16]. The aim of implementing RFWH is to improve water availability and thus enhance the ability to buffer water fluctuations. Furthermore, RFWH is designed to increase food self-sufficiency as a cross-sectoral impact. Taken together, RFWH has considerable potential to contribute to increased sustainability and the enhanced wellbeing of people in the region [17,18].

The exceptional duration of the project and its funding framework along with water harvesting as a highly relevant strategy for improving water security offered the ideal prerequisites for a systemised reflection on the implementation of all the steps in the transdisciplinary research approach. It offered new insights from practice into how transdisciplinarity and the SES concept are interlinked, and the consequences of this on the formulation of a research question and the design of research tasks on the ground.

This article starts with a presentation of the case study and the project setting, then outlines the conceptual and methodological approach of transdisciplinarity and the SES concept, before showing how this shapes and performs the implementation of RFWH. The applicability and limits of this approach are discussed and conclusions presented from a decade of project work.

2. The Namibian Case Study

2.1. Case Study Area

The CEB is the southern part of the transboundary Cuvelai catchment, which is shared by Angola and Namibia (Figure 1). The CEB covers an area of 34,723 km^2, representing 4.2% of the national territory. The climate in the CEB is classified as semi-arid, with one rainy season between October and March. Average annual rainfall varies between 200 mm in the southwest and 600 mm in the northeast [15]. The annual evaporation rates of approximately 2600 mm are extremely high [19]. Very variable rainfall and contrasting extremes result in either too much or too little water [9]. The climatic and topographic conditions in the CEB mean that the region lacks permanent water sources. Instead, the basin is characterised by a system of ephemeral rivers and small water courses (known as oshanas) that drain water from Angola into the Etosha Salt Pan in the south. The pan is located within the Etosha National Park, and water flow is crucial for the park's ecosystem and its high biodiversity. As the topography is flat and rainfall events are intensive, the basin is regularly affected by floods. The water quality of the oshana water degrades rapidly after the rainy season due to the high rate of evaporation and the uncontrolled use of water by humans and animals. Climate change is likely to pose additional challenges to securing sufficient water for ecosystems and people [20,21].

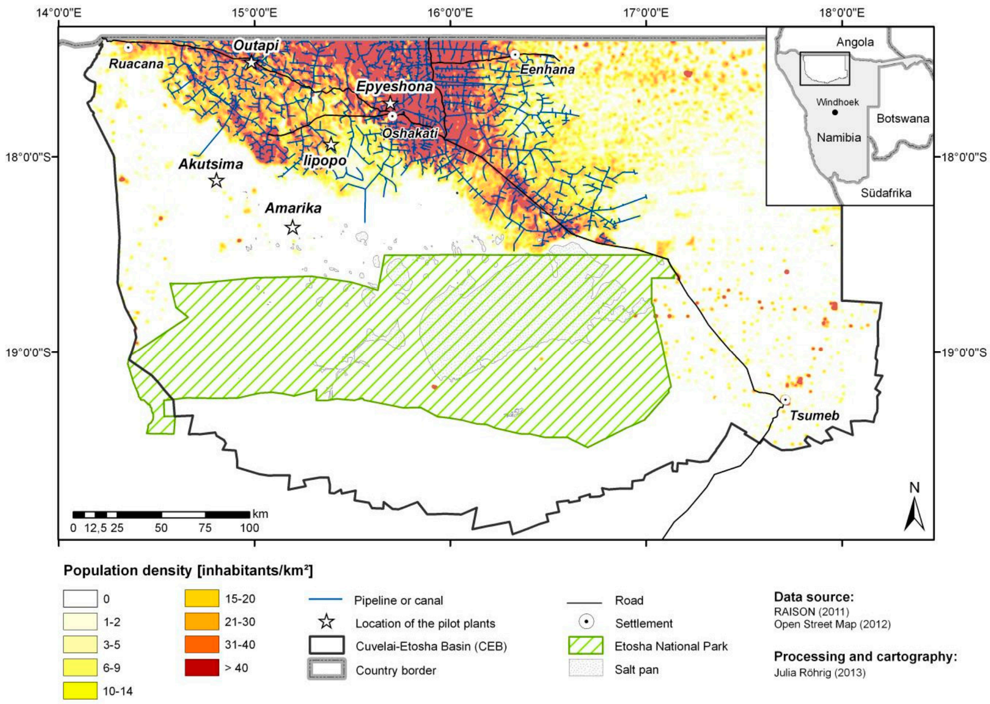

Figure 1. The study area in central northern Namibia and the location of CuveWaters pilot plants for all implemented technologies. The pilot sites for rainwater and floodwater harvesting are at Epyeshona and Iipopo.

Water availability has influenced settlement activities, land use and livelihood strategies for decades. The basin is the most densely populated rural area in Namibia and has around 850,000 inhabitants [15], which is almost half the population. These circumstances complicate the essential task of meeting basic needs for livelihood security, such as water and food supply. Thus precarious living conditions for the population and a sensitive dependency on the dynamics of natural conditions coincide with an ecosystem characterised by exploitation and scarcity.

The technological solution for supplying drinking water to the communities is a long-distance canal and a pipeline system fed by the Kunene River, the border river between Angola and Namibia. This transboundary and interbasinal water transfer is one of the largest supply networks in Africa [19,22]. Where the supply network ends, people depend on water from hand-dug wells or seasonal surface water and rainfall for seasonal agriculture, livestock farming and household consumption [23,24]. Apart from this long-distance infrastructure, water availability is unreliable and its quality degrades rapidly, especially during the dry season. Rainwater and floodwater harvesting for domestic use does not systematically occur in the CEB. In the 1950s and 1960s, pump-storage dams were constructed for floodwater harvesting, but high evaporation and inadequate soil conditions brought these attempts to an end [25,26].

In the basin, livestock farming is traditionally the predominant source of livelihood. It is complemented by rain-fed agriculture, primarily based on pearl millet (known locally as "mahangu") and fishing during the wet season [15,27]. Rainfall is not typically stored in the project region, therefore no crops are planted during the dry season, which means the productivity level is fairly low. Food security in the basin is therefore highly dependent on food imports from South Africa. These common practices and a low level of education mean that there is limited knowledge about the hydrological cycle, water quality or irrigation farming. In contrast, there is wide-ranging and valuable indigenous knowledge about disaster prediction and coping mechanisms based on close observation of animals, vegetation, weather and celestial bodies.

After the country's independence, the Namibian government began to draw up reforms to improve knowledge and practices with the aim of sustainably managing the scarce water and land resources under the paradigm of Integrated Water Resources Management (IWRM) [16,28]. This process has resulted in various changes to the institutional landscape. New organisations have been set up at different levels as part of the IWRM implementation strategy and decentralisation process. One example is the Basin Management Committees (BMCs), which represent all the stakeholders in their respective basins or sub-basins. The establishment of BMCs began in 2003, but despite considerable demand to strengthen the involvement of stakeholders, the creation of further BMCs is somewhat behind schedule [28]. While key water policies are in harmony with IWRM principles, their enshrinement in law is long overdue, which has weakened regulatory practice, reduced institutional empowerment [28] and hampered reforms aimed at including the local population in the management and financing of the water supply. As for food supply, local food production is regarded as critical for food self-sufficiency and security, and large-scale irrigation projects are being promoted to improve the production level and generate independence from imports [29,30].

2.2. The CuveWaters Project

From 2004 to 2015, the international research and development project "CuveWaters: Integrated Water Resources Management in Central Northern Namibia (Cuvelai Basin) in the SADC-Region" investigated how adapted technology-based solutions could contribute to IWRM in the CEB. A transdisciplinary research approach was applied based on the integration of science, technology and society [31]. This approach is reflected in the project design and structure: its empirical and technical components are closely linked to integrative societal elements, providing the basis for adaptive problem-solving since interlinkage promotes social embedding of the technologies along with the active involvement of the institutional players and local population.

The funding programme of the German Federal Ministry for Education and Research (BMBF) comprised three main project phases and a preceding six-month exploratory project phase. Each transition to the next phase was accompanied by an evaluation of the previous results and a proposition for the future project concept.

During the exploratory project phase of CuveWaters, key stakeholders in Namibia and technology partners in Germany were identified. The common goal was to establish a multi-resource mix for water use that was designed "to improve the living conditions of people in the project region" [31] (p. 689). The underlying methodological approach and implementation process are described in more detail in [9]. 'Multi-resource mix' means that water from different sources is made available as a result of adapted technological solutions, and then used as drinking or irrigation water depending on its quality. Three technological solutions were identified with the Namibian partners and marked the start of the multi-resource mix: rainwater and floodwater harvesting, and groundwater desalination along with sanitation and water reuse.

After the exploratory project phase, its implementation began in 2006 in three main phases—the initial, pilot and diffusion phases—and was completed by the end of 2015 [31]. The first and second main project phases were an interdisciplinary endeavour involving stakeholders such as communities and administrations. Using what is known as a demand-responsive approach [32], the technological design was jointly developed, appropriate sites were identified and pilot plants were implemented. The third main project phase focused on handing over ownership, disseminating acquired knowledge and evaluating it in terms of its contribution to societal and scientific progress. This provided the basis for safeguarding implementation on the ground for a period beyond the end of the project. However scientists, industry partners and policy makers were also addressed as target groups in order to scale up efforts and transfer the technologies to other regions.

3. Conceptual and Methodological Background

3.1. The Transdisciplinary Research Approach

Transdisciplinary research approaches are increasingly being adopted in research on resource management problems because they appear to be very well suited to addressing the complexity of pressing problems [8,9,33,34]. In the CuveWaters project, the approach of Jahn et al. [8] was applied. This approach shows a clear theoretical foundation [14] and exhibits a well developed implementation process based on a history of project experiences [8]. According to [8], three consecutive phases can be distinguished in an ideal transdisciplinary research process:

- Phase 1: formation of a common research object (problem transformation)
- Phase 2: production of new knowledge (interdisciplinary integration)
- Phase 3: transdisciplinary integration (evaluation of new knowledge for its contribution to societal and scientific progress).

Phase 1 comprises the sequence of two transformations, from the societal problem to a boundary object and then to an epistemic object from which research questions can be derived. Boundary objects have a loose structure and aim "to accommodate individual perspectives and meanings while at the same time maintaining an identity that is recognized by all parties involved" [8] (p. 5). In contrast, epistemic objects are much more structured and have a well-defined meaning and use [35]. SES are typically examples of an epistemic object [8]. In phase 2, the roles of researchers and stakeholders are clarified and an integration concept for the research designed and implemented. Disciplinary action and interdisciplinarity are crucial in this process and are understood as integral parts of transdisciplinarity. If an SES has been formulated in phase 1, this can guide and structure research design and implementation. Finally, phase 3 concerns the assessment of integrated results and provides products for science and society. The focus is therefore on contributions to both societal and scientific progress. All three phases were applied in the present case study.

The three transdisciplinary phases correspond to the project phases of the case study but are not strictly identical. The exploratory project phase relates to phase 1 of the transdisciplinary process, the first and second main project phases relate to different stages of succession in phase 2, while the third and final main project phase relates to phase 3, with a smooth transition between these phases.

3.2. The Social-Ecological Systems (SES) Concept

The SES concept formalises the relationships between nature and society [12]. On this basis, it can serve as a starting point for operationalising transdisciplinary research by creating a link to research practice [11,14]. The SES concept is presented as part of the Frankfurt Social Ecology and the results section below uses the case study to demonstrate how this concept can guide and structure a transdisciplinary project.

In recent decades, the SES concept has become increasingly important in the international discourse on sustainability science [35–39]. It is used to describe, analyse and model human-nature interactions. In the discourse on the SES concept, both the Stockholm-based Resilience Alliance and the work of Elinor Ostrom have played a leading role. Research by the Resilience Alliance mainly focuses on the adaptive management of ecosystems from a resilience perspective [37,40]. Ostrom and her colleagues conceive of SES as a general framework with which to analyse institutions and governance systems, and then apply this framework in particular to the area of common-pool resources [41] or questions of the systems' robustness [42]. However, more recent studies link and integrate the concepts of SES and ecosystem services (ESS) [12,43–46]. This development allows mutual reinforcement when it comes to systematically conceptualising their benefits to society and reveals the underlying structures and processes that drive it. The various types of services within the ESS concept also extend the potential to interlink different areas of critical human-nature interactions, such as water, food and energy supply.

In this article, the latter discourse is referred to in the integration of the SES and ESS concepts, and the conceptual work published by [12,43,47,48]. The above human-nature interactions are interpreted as 'societal relations to nature' [49,50], in accordance with the formal research programme of the Frankfurt Social Ecology [14]. SES are understood to be the translation of the theoretical framework into research practice [35]. As part of the Frankfurt Social Ecology research programme, the concept of SES [48] was interlinked with the concept of ESS back in 2008, and 'management' was explicitly integrated to address the societal influence on nature. Both management and ESS form a dynamic regulatory cycle of complex interactions between actors and ecosystem functions (Figure 2). Together they allow an integrated analysis of how ecosystem-based benefits support society under changing conditions such as modified management strategies, but also climate change or biodiversity loss, as a function of the underlying research question.

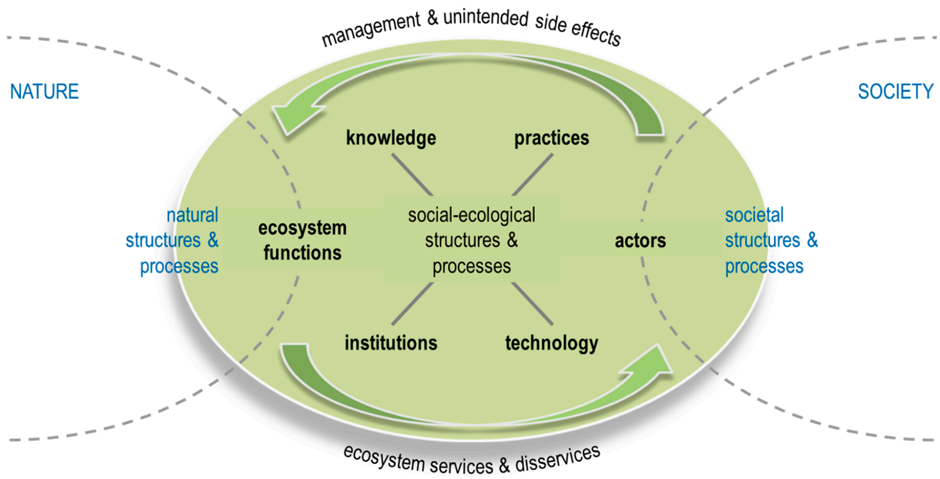

Figure 2. The concept of social-ecological systems (SES) [12].

SES (green circle) are defined as hybrid and emergent systems that are nested in both society and nature. In contrast to other concepts [39], SES here are not understood as a mere additive overlap of the natural and societal sphere. Although the relevant natural and societal structures and processes are part of SES, an additional hybrid social-ecological sphere is at the centre of SES [43,48]. This hybrid sphere is interpreted as an emergent outcome of highly nested interactions between various components over space and time; it shows its own specific social-ecological structures and processes which cannot be attributed to the natural or societal sphere or merely to the area in which they overlap. Nonetheless, SES also draw on those societal (social, economic, cultural and political) and natural (biological, geological, chemical and physical) structures and processes that are relevant for the considered focus of research. The general nonlinearity of SES, along with the multitude of interacting structural components and feedback processes, gives rise to their characterisation as complex, adaptive systems.

'Social-ecological structures and processes' determine the analytical core of SES. Examples are processes such as seeding, irrigation, harvesting, ploughing and extracting water, or structures such as gardens and waterholes. A further analysis of these structures and processes is offered in early works by Hummel et al. [48]. They identify knowledge, practices, institutions and technology as mediating dimensions (also called contextual factors) between society and nature. These dimensions are referred to here and their specification refined with regard to a clearer emphasis of their hybrid character. In this context, 'knowledge' comprises all forms of understanding by scientists and non-scientists referring to nature-society interrelations. Societal 'practices' represent routinised types and patterns of behaviour regarding the use of ESS in their material or symbolic relevance. The term 'institutions' addresses the fields of economy, politics, law and culture that create a regulatory system of rules for action with regard to the use of ESS. 'Technology' refers to all man-made material structures and developments that are designed and applied in order to interfere with ecosystem functions with the aim of making specific services available for use [43,47] (modified).

The key components of SES are actors and ecosystem functions. 'Actors' are defined here as persons and groups of persons who influence management and, subsequently, ecosystem functions with their actions, or who are affected by changes in ecosystem functions, services or disservices. The influencing and receiving quality of the interaction can vary for each actor. Actors can come from certain functional groups of society such as consumers, traders, farmers, resource managers and policy makers with respective interests and motivations. In addition, scientists can also be actors if it is assumed that the knowledge produced by research interferes with the activities of the other actors. 'Ecosystem functions' meanwhile are defined as the capacity of natural processes and components to provide goods and services that satisfy human needs, directly and indirectly [51]. They are a generic part of the natural dynamics and, as mentioned above, are subject to changes caused by societal management actions.

Finally, 'ecosystem services' comprise the benefits to society derived from ecosystems [51–53]. 'Ecosystem disservices' are interpreted as the opposite of ESS in the sense that they cause harm to society (e.g., financial or health risks and food insecurity). They are therefore perceived as negative factors for human wellbeing [54]. Actors influence the system either directly or indirectly via intended 'management' activities or their 'unintended side effects'.

4. Results—Transdisciplinary Implementation of Water Harvesting from an SES Perspective

This section refers to the technology of rainwater and floodwater harvesting to illustrate the practical implementation of the above-mentioned transdisciplinary research process. Here, the SES concept is applied in its heuristic and analytical functions to structure both the problem and the research process.

4.1. Phase 1: Formation of a Common Research Object (Problem Transformation)

4.1.1. RFWH as the Boundary Object

The exploratory project phase presented the first opportunity to develop and strengthen a network of contacts with key Namibian stakeholders. Discussions took place with representatives from the Namibian Ministry for Agriculture, Water and Forestry (MAWF), the Desert Research Foundation of Namibia (DRFN), Oshakati Town Council, Oshikoto Regional Council, potential users and other experts in Namibia and Germany. These discussions led to the identification and consolidation of rainwater harvesting and sub-surface water storage at household and community level as technologies of a so-called multi-resource mix. At the end of the first main phase of the project, sub-surface water storage became floodwater harvesting: modifications to the technical concept necessitated a change in name and henceforth only the term 'floodwater harvesting' will be used. Since the management and use of rainwater and floodwater have very similar characteristics, they were treated and analysed together. Important arguments for the joint agreement on RFWH as the common object of work were:

(i) the potential to make use of an unused water resource, (ii) its low complexity, (iii) the combination with gardening and thus its contribution to food self-sufficiency and income generation, and finally (iv) the high interest of potential users.

At this stage, RFWH enabled cooperation between the heterogeneous group of actors and therefore could be interpreted as the boundary object of subsequent research.

4.1.2. The SES 'Small-Scale Food Production System' as the Epistemic Object

At the early stage of the exploratory project phase, RFWH included plans for the use of the harvested water for gardening. Therefore, RFWH can be understood as a small-scale system within an overarching system for coupled water and food provision. The aim of introducing harvesting and storage of rainwater and floodwater for all-season gardening was to create a completely new opportunity for the productive and efficient use of local water and land resources. However, it was not intended for RFWH to substitute other forms of supply, but rather to generate an additional source of decentralised production and income. This technology was not widely available in the region at the time and was to be implemented with local material and capacities. Considerable potential for widespread implementation and diffusion was therefore expected.

The application of the SES concept, which commenced in the exploratory project phase and was subsequently continued, embedded the principal technological idea of RFWH (the boundary object) into a broader and structured context. The systems perspective on the coupling of water and land management practised in RFWH shifted the focus to the ecosystem service of 'food' and triggered an investigation from an integrative perspective (Figure 3). The SES concept allowed a stronger, more structured epistemic object to be created.

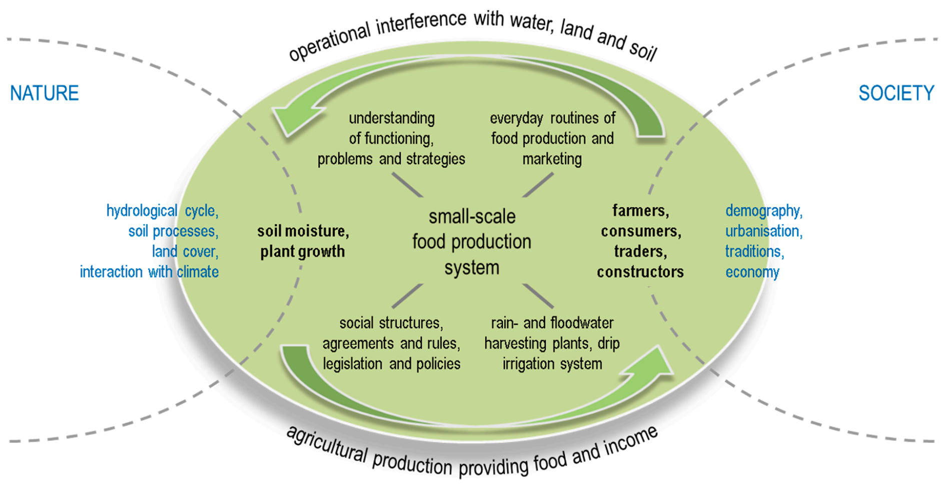

Figure 3. Application of the concept of social-ecological systems (SES) to the given case study of rainwater and floodwater harvesting as part of a small-scale food production system. At this level, SES serve as an epistemic object for research and can be understood as provisioning systems.

From a systems perspective, household farmers are primary 'actors'. Furthermore, food consumers, traders and construction workers also play a central role in generating the demand for locally produced food, as well as for income and labour. The key 'ecosystem functions' are water storage in the soil and primary plant production. They depend on numerous processes that regulate nutrient and water fluxes and determine biomass production. Actors and ecosystem functions are interlinked in a feedback loop. The primary demand for food drives water and land 'management', which in turn influences ecosystem functions and generates agricultural products as the key 'ecosystem service'. Consequences of management interventions include changes in the natural structures and processes such as the hydrological cycle (e.g., water buffering and reduction in run-off), soil processes (e.g., moisture and nutrient distribution) and land cover (e.g., cultivation of crops and land consumption of harvesting and storage components). Potentially 'unintended side effects' of management with possible adverse effects on ecology could be the introduction of new vegetable plants as invasive species in the region, the application of pesticides that are harmful to human or ecosystem health, soil leaching and reduced groundwater recharge due to water retention. Beyond the scope of this study, there are other long-term side effects of intensive and widespread land management, such as changes to local weather systems or landslides. Subsequent benefits of the key 'food' ecosystem service are primarily nutrition, health, income and labour. Managing the ecosystem and receiving its services further generates cultural benefits with regard to knowledge acquisition and environmental education, as well as the adaptation and enhancement of cultural farming traditions. 'Ecosystem disservices' may occur if, for example, new pests are introduced and distributed as a result of gardening activities.

The four mediating dimensions will be explained and exemplified below with regard to their role in the design of an integrated concept for research.

4.1.3. Defining the Research Question

Understanding RFWH as a boundary object and applying the SES concept helped define the epistemic object and identify the research question 'How do the two harvesting technologies need to be adapted to and embedded within the complex social-ecological context in order to provide the basis for the diffusion of a sustainable and complementary source of water, food and income?' This pivotal research question entailed further research questions such as: What are the particular needs of people when it comes to designing rainwater and floodwater harvesting plants? What forms of governance are appropriate in socio-cultural and institutional settings? What suitable ways might there be to develop the capacities of people and institutions? What economic perspectives exist based on cost-benefit considerations and options for financing? What are the potential adverse ecological effects?

4.2. Phase 2: Production of New Knowledge (Interdisciplinary Integration)

4.2.1. Clarification of the Roles of Researchers and Stakeholders

Before starting the actual work, it was important to clarify the respective roles and responsibilities of the researchers and stakeholders. The role of researchers was to put the transdisciplinary approach into practice on the basis of a sound methodology. To achieve this goal, they had to secure the participation of stakeholders in the research, planning and implementation phases. This demanded a high level of integration without compromising the efforts of the various disciplines. Stakeholders performed the role of knowledge holders, experts and supporters. They had the task of ensuring that RFWH was implemented taking into consideration relevant policies and questions of governance, everyday practices and restrictions, and socio-economic and cultural conditions and constraints. In an advanced phase of the project, ownership of the pilot plants had to be adopted by a Namibian stakeholder. A lengthy process preceded the assignment of this very specific role. During this process, it was jointly decided that the communities themselves, or more precisely the traditional authority represented by the headman, would take over responsibility for the facilities. The Agricultural Extension Services of the MAWF were assigned the task of ensuring that the users received assistance. Finally, the northern campus of the University of Namibia (UNAM) in Ongwediva took over the role as the centre for capacity development and technical studies on RFWH.

4.2.2. Design of an Integration Concept for Research

As a result of phase 1, which involved applying the SES concept in order to define the epistemic object, it became evident that the implementation of reliable rainwater and floodwater harvesting 'technology' had to include knowledge, practices and institutions in order to guarantee sustainability (Figures 2 and 3).

Although water harvesting is a relatively simple technology, those building it require specific 'knowledge' (know-how), as do the farmers who operate and maintain the facilities, including the gardens, in order to generate yield and profit. For instance, they need to know the optimal times for sowing, harvesting and selling. The respective actors have to understand how the plant is structured and how it functions, as well as its interactions with external factors. The actors need to possess specific problem-solving skills, which means that after understanding the problem, they are able to weigh up solution strategies and alternatives, and act on the basis of the decisions made.

Knowledge paves the way for new 'practices' and is therefore an integral part of stakeholders' actions and everyday routines. At the same time, practices contribute to long-term experiences and the deeper understanding of system dynamics. It becomes evident that practices predominantly address the question of 'how', while knowledge addresses the question of 'why'. Practices mainly cover the areas of water collection and storage, gardening and marketing. These areas of activity are right at the interface of society and nature, and therefore notably exhibit their immanent hybrid character: they are triggered by societal demands for benefits and their respective ESS, they are strongly influenced by social, economic and institutional considerations, and they have an impact on the water cycle, soil structure and land cover.

'Institutions' are relevant in order to sustainably embed implementation, safeguard the results and initiate early and effective diffusion processes within a favourable environment [55]. When selecting suitable locations for and designing such facilities, the active involvement of local and regional stakeholders and their institutional background is essential to meet local demand and ensure all-round commitment. Particularly in community-orientated approaches, institutions play a decisive role in safeguarding compliance with norms and rules, securing adherence to legislation and policies, or establishing suitable communication strategies to resolve conflicts. In the Namibian case of RFWH, the traditional authorities represented by the headmen took ownership of the communal harvesting plants. Farmers' groups and traditional authorities signed a mutual agreement that set out the rules and responsibilities. On the ministerial side, the Extension Officers of the Directorate of Agricultural Production, Engineering and Extension Services (DAPEES) at the Ministry of Agriculture, Water and Forestry (MAWF) had the task of providing regular assistance on farming and financing issues, including possible subsidies, and training opportunities. IWRM-related institutions such as the BMC were still in the development phase as far as the development of structures and capacities was concerned. Those institutions were involved but not yet able to play a strong role in RFWH. Instead, other non-IWRM-related local institutions such as the Rural Development Centres (RDC), Constituency Councils and Agriculture Development Centres (ADC) came to the fore, acting as promoters, supporters and sponsors since RFWH in combination with gardening serves their interests with respect to community development. On an overarching regional and national level, institutions needed to be involved in the process in order to develop standards and funding models to further support scaling up the processes. They were also required to embed the new technological concepts in strategies and policies for water, agriculture and food production, climate change adaptation and questions of property rights.

This had consequences on the design of the research process with respect to the areas of core activities. All the four mediating dimensions explained above needed to be addressed and integrated. They therefore constituted four areas of activities for research. Furthermore, transdisciplinarity with the methodologically guided involvement of stakeholders in a participation process was chosen to constitute a fifth core activity. Finally, the performance of empirical studies with respect to different, more discipline-based tasks was an additional core activity in the project. Thus, the following six core activities structured the research of CuveWaters:

- technological development
- knowledge management
- capacity development
- governance and institutionalisation

- participation
- empirical studies.

These core activities were strongly interlinked since participation, for example, contributed to all the other activities. The structure in Table 1 represents this interlinking.

4.2.3. Implementation of the Research Process

The core activities comprised a rich repertoire of methods and tasks (Table 1). Here, integration became evident since the core activities not only referred to their own corresponding mediating dimension within the SES concept, but also contributed to the other dimensions. This is the core structural element of integration in the research process.

Table 1. Integration concept for research and repertoire methods and tasks showing how the core activities of the transdisciplinary research process contributed to the mediating dimensions of a sustainable implementation from an SES perspective.

Core Activities	Mediating Dimensions			
	Knowledge	**Practices**	**Institutions**	**Technology**
Technological development	Generation of knowledge about technological solutions (engineering sciences)	Provision of information about requirements for construction, operation and maintenance	Provision of information about technical specifications for planning and decision-making (e.g., costs, production capacities)	Construction of pilot plants, adaptation and optimisation of technologies to the specific social-ecological conditions
Knowledge management	Development of manuals, planning instruments and toolkits; public relations; drafting of scientific publications	Provision of knowledge-based instruments for planning and decision-making; development of informative toolkits for operational practice	Provision of knowledge-based instruments for planning and decision-making; development and transfer of implementation concepts	Development and implementation of analytical tools for monitoring and interpreting the plants' technical status
Capacity development	Training and knowledge transfer (e.g., manuals and toolkits); academic training with lectures and summer school, scientific theses & internships	Training for improved skills of farmers and constructors; supervision of scientific theses & internships to improve IWRM practice; community health clubs	Training for institutions (train-the-trainer) for ownership, implementation and operation, scaling up	Training for technical service providers and technical staff
Governance and institutionalisation	Stakeholder and policy analysis; literature review; development of implementation concepts including recommendations for future implementation and scaling up	Establishment of responsibilities for training programmes (e.g., for plant construction, small-scale gardening, marketing)	Continuous communication and cooperation; institutional embedding incl. ownership, implementation support and legal safeguarding; development of financing models	Development of adapted technical standards; initialisation of standardisation (e.g., tank materials, safety requirements)
Participation	Community/farmer workshops; user involvement in monitoring & evaluation	Community/farmer workshops; demand-responsive approach	Involvement of institutional representatives; demand-responsive approach	Adaptation of pilot plant designs; pilot construction under real-life conditions with local workers
Empirical studies	Monitoring & evaluation; social-ecological impact assessment; financial analyses and economic impact studies	Optimisation of practices (e.g., fertiliser use, crop selection, efficient irrigation); studies on socio-cultural perspectives on water	Adaptation of institutions (e.g., responsibilities, rights, operation); analysis for substantiated arguments (e.g., economy)	Optimisation of technological components

As part of the 'technological development', different rainwater and floodwater pilot plants were established to investigate whether the technologies were feasible options for improving livelihoods in Namibia on the basis of scientifically derived evidence. Rainwater harvesting plants have been in operation at Epyeshona in the peri-urban surroundings of the town of Oshakati since 2010 [32,56,57].

The criteria for the plant design were a mean precipitation of 470 mm/a and, as a result of the socio-empirical survey, a demand for gardening space amounting to 150 to 230 m^2 per farmer, as well as the availability of catchment areas for rainfall harvesting. Two technical and organisational options were tested with regard to their potential to meet people's needs: at household level, three pilot plants harvested rainwater from roof catchments and stored it in tanks (30 m^3) for use in household gardens, while at a community level, rainwater was harvested from a ground catchment and a greenhouse roof, stored in different reservoirs (in total 200 m^3) and used for irrigation by six households in a joint management initiative. Given the variability in rainfall, these designs should have allowed gardening with full storage capacity in approximately three out of four years. In-depth analysis of different gardening options using a tank flow model and an irrigation water model showed that even the negative impacts of climate change could be offset partly or completely by specific adaptation measures [58].

Floodwater harvesting was implemented at Iipopo in 2012 [57] based on similar assumptions regarding the gardening area demand per farmer and with the constraint that only a marginal amount of discharge from the oshana should be captured so as not to compromise its regular flow. Here, water from the oshana was pumped into different storage reservoirs (in total 400 m^3) during the rainy season, when the water quality is at its best. The stored water was used for irrigation by up to ten households on a cooperative basis. All the plants had a water-efficient drip-irrigation system installed. Despite experience acquired in the 1950s and 1960s with what are known as Stengel dams (storage capacities between 25,000 and 100,000 m^3), the project's rainwater and floodwater harvesting technologies were new and innovative in the region.

In order to share and disseminate the experiences and results from the project, different activities were conducted under the umbrella of 'knowledge management'. This project component comprised in particular the development of instruments to support decision-making and planning processes. By developing such tools, the project wanted to ensure that the essential results and experiences of the project were made available to decision-makers or planners in a practical and suitable way beyond the duration of the project [59]. In particular, a toolkit for rainwater harvesting was designed jointly with Namibian partners. The final version of the toolkit consisted of applied information for all phases in the planning, construction and operation of the technology.

The aim of the academic and non-academic 'capacity development' activities was to improve and transfer knowledge and practices at all levels. The project therefore ran about 30 training courses for rainwater and floodwater harvesting and subsequent gardening. Farmers were trained to operate and maintain the facilities beyond the end of the project, but also to regulate social conflicts within the new setting of community management. People were trained in the construction of harvesting and gardening facilities, which was also an investment in working skills and job creation.

The 'governance and institutionalisation' side of the project comprised a stakeholder analysis, a review of relevant political documents and a policy analysis. Such analyses together with continuous communication and exchange provided strong back-up for the incorporation of the project activities into current regional and national planning activities. In the long term, it supports the political and legal safeguarding of users and could foster future dissemination processes [56]. By strengthening local food production, the project contributed to blueprints such as Namibia's Vision 2030 [29] and Millennium Development Goals No. 1 and 7 [60].

Concepts that are purely technologically sophisticated can easily clash with users' socio-cultural needs and practices. 'Participation' is essential to meet existing needs and to embed new technologies. Different activities ensured that stakeholders were actively involved in the planning, implementation and evaluation processes, as well as in operational structures. Therefore, a new participatory method—the demand-responsive approach—was jointly developed with the Namibian partners (for details see [32,61]).

The project's 'empirical studies' project generated valid and fundamental information and data to identify impacts on SES as a whole, evaluate their sustainability and further adapt the technologies. Efficient and feasible pilot plants were an essential basis for facilitating their adoption by Namibian partners and were therefore crucial to dissemination. For optimisation and evaluation, a comprehensive socio-technical monitoring programme was developed with the communities at every project site. For instance, cost-benefit analyses at household level identified 'ferro-cement' to be the most cost-efficient material for tank construction [56]. Furthermore, empirical studies were crucial in addressing questions raised by stakeholders or institutions about how to adapt implementation in future. They also identified the risks and uncertainties for all parties, particularly regarding economic considerations such as investment, operation and maintenance costs.

4.3. Phase 3: Transdisciplinary Integration (Evaluation of New Knowledge for Its Contribution to Societal and Scientific Progress)

What contributions were made to societal and scientific progress? The main achievements were the successful implementation of RFWH, the adoption of responsibilities as part of the ownership process, and the establishment of everyday use of this technology. Appropriate storage volumes allowed small-scale gardening throughout the year, enriched and diversified the farmers' diet, and allowed income generation by selling the harvest at nearby markets [56]. Jobs in plant construction and gardening activities could be created and a stimulus for the regional economy generated [56]. Reduced dependence on food imports from South Africa was also expected. Additionally, the research and development process also provided new opportunities to acquire self-confidence and social acceptance. Apart from water and food security, the project therefore addressed an improvement in the socio-economic and health situation and, furthermore, the enhancement of knowledge and practices relating to natural resources management including gardening [32].

All the mediating dimensions played their part in this achievement: the technological development of a variety of solutions for different conditions and forms of application [62,63], the establishment of ownership and governance structures [64], training and other instruments for capacity development such as the RFWH toolkit [65], studies on the impact of alternative gardening variants and the contribution to adapting to climate change [58]. A significant proportion of the references used were clearly non-academic, which is a typical and often underrated (societal) outcome of transdisciplinary research.

The acceptance and pioneering nature of this technology—as important signs of societal progress—were impressively reflected in the term 'Green Villages', which was given to the pilot sites of Epyeshona and Iipopo by the Namibians themselves. They also used the term as a brand in order to boost the sales of their harvest at market. The respective communities became model sites for other communities and additional rainwater harvesting plants have since been implemented, initiated by single households and by Namibian institutions. The project supported these additional implementations via indirect consultation only. As also stated by Vreugdenhil et al. [55], the flexibility of the existing pilot schemes was a critical requirement for adapting the RFWH technology to different fields of application and varying conditions. As mentioned above, one of these additional plants has been implemented at the UNAM northern campus, funded by the Gesellschaft für Internationale Zusammenarbeit (GIZ), and is being used for academic education and technical studies.

A technology toolkit for RFWH was developed that contains information for planning and detailed technical manuals for construction, including materials and tools lists [65]. The toolkit is intended for technical experts (e.g., Agricultural Extension Offices and Rural Development Centres) and supports future capacity development such as training and knowledge dissemination. It also ensures the sustainability of RFWH because the pilot plants have increasingly become role models for further dissemination.

At the interface with policy, outcomes and recommendations addressed the cross-sectoral benefits of RFWH, the reduced dependency on climate variations and effects of climate change, as well as the need for state or donor-financed training and dissemination centres [18,56]. The latter created a setting that promotes small-scale water harvesting and gardening initiatives and enables them to be diffused in a self-organised manner [18]. However critical points were also mentioned. For example, the initial investment required may be not affordable by considerable parts of the population, and regional, national or even international financing options should be considered for the promotion of RFWH.

The pivotal research question of how water-harvesting technologies need to be adapted and embedded were answered by these outcomes. Solutions of a flexible technical design (rainwater or floodwater, aboveground or underground tanks or alternatively ponds, different catchment areas and storage volumes, variants of tank material) and a flexible management approach (individual or community) were key in terms of technology. However, just as important in the process was the close involvement of users and the responsible institutions guided by the methodology [32]. At the same time, the development of a demand-responsive approach together with the Namibian partners and the deliberations on the application of the SES concept for bringing transdisciplinarity into practice contributed to the scientific progress that was made.

5. Discussion

This study demonstrated how the transdisciplinary research concept developed by Jahn et al. [8] could be applied to a case study concerning the implementation of RFWH in central-northern Namibia. Here, the application of the SES concept played a crucial role. The SES concept facilitated the formulation of the epistemic object for research by structuring the problem situation (and boundary object). The concept then served as a basis for the research design and thus guided a solution-oriented research process. The transdisciplinary approach and SES concept were closely interlinked and complemented one other. While the transdisciplinary approach was manifested in a strong procedural influence on the research due to the respective phases and steps inherent in it, the application of the SES concept strongly guided the systemic perspective, the structure of tasks, the methodological repertoire and its integrative dimension, and disciplinary composition of the project.

The implementation of such an ideal transdisciplinary research process is still an exception rather than the rule. One major reason is that this kind of research process is quite time consuming and funding schemes are usually still not adequately adapted to the requirements of this mode of research. The case study presented here began with an open concept, and only the intense involvement of the stakeholders in a series of workshops and consultations allowed the demand for RFWH to be identified and concrete socio-technical design of suitable variants of RFWH in combination with gardening to be developed. The subsequent implementation on the ground was followed by extensive measures around capacity development in the construction, operation and marketing of the products, advice and support to the pilot facilities, the establishment of community management schemes and strategies for conflict solution that were new to the people in the area. The associated changes in the communities and for other stakeholders were judged to be new and essential structures and processes, thus the introduction of RFWH as a technological innovation worked hand in hand with the respective innovations in society. Finally, the adoption of ownership took a considerable time before and after the mere technical implementation. Funding conditions often do not allow the thorough implementation of all steps of the whole transdisciplinary process and involve the risk of projects struggling with long-term sustainability if they are constrained to parts of the process. Thus, an adaptation to the funding frameworks is the first critical factor for the complete operationalisation and success of transdisciplinary approaches.

The present case study demonstrated that the SES concept played a central role in the operationalisation of transdisciplinarity. The SES concept used here originated from the Frankfurt Social Ecology [14]. The current literature on SES is diverse and the underlying goals, disciplinary backgrounds, addressed scales and levels of differentiation vary considerably [66]. However, the authors argue that this diversity is important in order to reflect the complexity of research questions and problems. The concept presented in this article builds on a balanced view of the mediating dimension of knowledge, practices, technology and institutions, and highlights their key role in the dynamics between actors and ecosystem functions, with management and ESS as symmetric counterparts. Concepts of human wellbeing or the valuation of ESS can be integrated as further analytical differentiations for the unspecified societal structures and processes behind the actors' component. Those concepts can also be related to the four mediating dimensions, e.g., the valuation of ESS is interlinked, *inter alia* with knowledge and institutions. In contrast, Ostrom [36] focuses strongly on questions of governance and introduces a framework with multi-tier variables for a thorough analytical perspective. Authors such as Bennett et al. [67,68] and García-Llorente et al. [69] place ESS at the centre of SES. They shift the focus to the interrelation and trade-offs of ESS as a function of societal drivers [68,69] or at the valuation of ESS [46]. Finally and critically, it depends on the given social-ecological issue and research question as to which conceptual approach is most suitable for structuring and guiding the transdisciplinary research process.

As discussed, the presented approach provided guidance for the research process towards a combination of technological and social innovations. Another issue of considerable importance was the challenge of intercultural integration and collaboration. Different knowledge backgrounds, forms of communication, conflict management, institutional structures, perceptions of water and nature, value systems and traditions exist in parallel when jointly working on RFWH as the common boundary object. In this regard, the strong participation of stakeholders and consideration of local demands and views about the issues supported the project's ambition to address this challenge. As an example, a team of Namibian experts, project partners and advisors analysed the heterogeneous perspectives of water held by the three groups of Namibian-German project facilitators, community members and local authorities. They found that the perceptions differ—even between Namibian stakeholders—with regard to the questions of the 'infinity of water resources' and 'water as an economic good', while the roles of women and participation were not disputed [70]. This reinforced efforts in knowledge integration and transfer or participation, and influenced the themes and priorities of subsequent activities such as community workshops and studies. In general, the broad repertoire of methods and tasks represent the wide perspective of the transdisciplinary approach, which includes awareness of a project's intercultural endeavours in the context of research and development.

6. Conclusions

The application of the SES concept in this study shows that innovations in technologies alone are not sufficient to drive a system's overall sustainability. To make a system more sustainable in the long run, the introduction of new technologies must be accompanied by appropriate developments in knowledge, practices and institutions, all of which are crucial to the system. Located at the interface between the societal and natural spheres, these dimensions of action display a hybrid character. They are an expression of the complexity of the system, which needs to be taken into account when structuring and conducting the research (and development) process. Thus the results of this study also show that the technological activities must be supplemented by various accompanying activities, such as knowledge management, capacity development, governance and institutionalisation, participation, and empirical studies. These activities represent and address the aforementioned dimensions of the SES concept in action and further principal tasks of research. It becomes apparent that innovations in technologies are underpinned by corresponding changes in society, more specifically by social innovations.

The study further demonstrates how the SES concept helps to structure transdisciplinary research. The results from the Namibian case study highlight that the SES concept serves as an epistemic object, but also guides the design of the research process. It has an integrative function in terms of permitting analysis of different (basic) societal relations to nature in areas such as nutrition, land use or labour and production. In the case study, the provision of water and food was approached by relating resource management and ESS to their societal benefits, actors and ecosystem functions.

Furthermore, linking the SES concept with the ESS concept explicitly addresses the dynamic feedback loop between actors and the ecosystem functions of SES, and relates it to a clear conceptual framework. It also captures a broader system-related perspective for the ESS concept and thus allows a more comprehensive analysis of drivers and responses to changes in ESS.

Additionally, the system approach allows generalities to be deduced and also helps generate new knowledge about the question of transformation and how to shape the process towards sustainable water management, as presented here. Both are important for the dissemination of integrated solutions. However, the transferability of the pilot plants remains a challenging task and still carries uncertainties. The promotion of scaling up processes such as the development of funding models, the evaluation of all dimensions that are crucial to the respective SES, and reflections on the degree of adaptation required for transfer to other contexts are vital for long-lasting success beyond the duration of the project.

Finally, conducting and implementing transdisciplinary research requires relevant funding schemes. If the goal of the sustainable and long-lasting success of such a research process is to be taken seriously, there is an urgent need to adapt current research funding because transdisciplinary research is much more time consuming than fundamental research. The case study presented here, which lasted around ten years and included a funded exploratory project phase, is still the exception rather than the rule.

Acknowledgments: This study was funded by Germany's Federal Ministry of Education and Research (BMBF) (CuveWaters project, grant numbers 0330766A, 033L001A, 033W014A) and the 'LOEWE' (Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz) research funding programme of Hessen's Federal Ministry of Higher Education, Research, and the Arts (BiK-F). Special thanks to the CuveWaters project partners in Namibia and Germany, in particular to Alexander Jokisch from the Technische Universität Darmstadt, for discussing details on harvesting technologies. We also thank our colleagues at ISOE, Diana Hummel, Thomas Jahn, Alexandra Lux, Robert Lütkemeier and Engelbert Schramm, for their conceptual input to SES. We are very grateful to Maxine Demharter, Heidi Kemp and Claire Tarring for proofreading this work. We would like to thank our colleagues from BiK-F, Karen Hahn, Katja Heubach, Thomas Hickler, Lasse Loft and Uwe Zajonz, for the discussions on earlier versions of the SES concept. Finally, we express our gratitude to the reviewers for their very helpful and constructive comments.

Author Contributions: Stefan Liehr and Julia Röhrig wrote the introduction and the sections on the Namibian case study and results. Stefan Liehr and Marion Mehring formulated the conceptual and methodological background. Stefan Liehr discussed the results. Thomas Kluge, Stefan Liehr and Julia Röhrig elaborated the conclusions. The revision was conducted by Stefan Liehr.

Conflicts of Interest: The authors declare no conflict of interest.

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