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# Urban Water Crises under Future Uncertainties: The Case of Institutional and Infrastructure Complexity in Khon Kaen, Thailand

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**Abstract:** This paper uses the emerging crises in water management in North East Thailand as a case study to examine the effectiveness of existing institutional structures and processes to adapt to an uncertain future climate. We argue that it is through an analysis of the interface of actors, institutions and physical infrastructure that climate vulnerability can be better understood, and conversely, that climate resilience might be strengthened. This research has global significance as case studies of emerging water crises provide valuable insights into future vulnerabilities and the Thailand experience speaks to similar challenges across the global South. Our findings illustrate that water managers on the front line of dealing with climate variability are constrained by the interaction of infrastructure that was designed for different times and needs, and of institutional structures and processes that have emerged through the interplay of often competing organisational remits and agendas. Water management is further constrained by the ways in which information and knowledge are generated, shared, and then applied. Critically the research finds that there is no explicit consideration of climate change, but rather universally-held assumptions that patterns of water availability will continue as they have in the past. As a result, there is no long-term planning that could be termed adaptive, but rather, a responsive approach that moves from crisis to crisis between seasons and across years.

**Keywords:** urbanisation; climate vulnerability; complex systems; resilience; water governance

## 1. Introduction: Confronting Crises in Water Management

Alternating between floods and droughts since the 2011 flood 'disaster' [1], the case of Khon Kaen exemplifies many of the climate-related challenges that cities face in Southeast Asia and monsoonal regions of the globe [2–6]. The uncertainty of water availability coupled with growing demand for water across different uses and locations create enormous challenges for the agencies responsible for making decisions on storage and distribution [7,8]. In this context, the ways in which increasingly complex physical infrastructure and institutional arrangements function are key determinants in how climate vulnerabilities become manifest. Recent experience of how different actors have addressed these kinds of challenges provides valuable insights into the characteristics of vulnerability and the potential impacts of climate-related shocks and crises, while also opening up discussion on potential mechanisms that address the level of uncertainty and future risk [9–11].

The research presented in this paper focuses on a city in North East Thailand that is emblematic of challenges facing urbanising areas across the global South. Like many cities in Thailand, Khon

Kaen is growing rapidly, attracting considerable investment in real estate and expanding its area into the rural periphery. The government established Khon Kaen as a Secondary Urban Centre for industrial development 50 years ago as part of a national policy direction to ease the congestion of Bangkok [12]. This urban growth has accelerated more recently, with regional drivers of change exerting their influence on Khon Kaen's. The city is positioning itself as a regional gateway, taking advantage of communications infrastructure that connects it with the Greater Mekong Sub-region (GMS) and further planned investments in high-speed rail, as well as expansion of the airport, serving both national and international links [13].

Yet as the city grows it is already experiencing the adverse impacts of urbanisation and climate variability that puts its long-term sustainability in jeopardy. This is most clearly illustrated through the case of water. Although Khon Kaen is one of the largest, fastest growing, cities in Thailand, 62 percent of the provincial area remains rural/agricultural [14]. It is these areas that have been worst impacted by the prolonged water crisis of recent years. To maintain minimum supplies for domestic water use and industry, as well as maintaining environmental flows, the needs of farmers are sacrificed. In times of flood, rural areas are inundated to protect urban areas, while in times of drought; irrigation is restricted or shut down completely. Farmers have now experienced several years without adequate access to irrigation supplies, despite having intensified their agricultural practice over the last twenty years based on assumptions of irrigation availability [15]. The provision of irrigation water has been the cornerstone of agriculture development for Khon Kaen, and the North East, appearing in state policy narratives as facing a crisis of water shortage [16].

As with most other parts of Central, Northern and North-eastern Thailand, Khon Kaen was impacted by the dramatic floods of 2011 only to then have five years of back-to-back droughts, which culminated in the intense dry season of the 2016 El Nino. Coming out of the El Nino period, the city then experienced intense rainfall and flooding associated with the La Nina of late 2016 [17]. By November 2016, rural farming areas and 200 households in 11 districts along the Chi River were flooded. Some areas were flooded two or three times between the end of June and November [18,19]. Emergency relief was provided to affected households, including electric pumps to divert and drain floodwater. Farmers were permitted to grow rain fed rice crops in August and September, but unexpected heavy rain during the harvesting season in early November caused damage and losses of the rice crop [20].

Though subject to some degree of uncertainty, climate scenarios project a pattern of longer, more intense, dry seasons; followed by shorter rainy seasons with more intense rainfall. A pattern of alternating floods and droughts is therefore projected to continue [21,22]. All the while, demand for water is set to rise as the number of urban consumers grows and industry expands, against a backdrop of continuing high demand for irrigation water. With water also contributing to energy production, the pressures on ensuring equitable allocation of water between competing needs will intensify. Such pressure on water resources is exacerbated by the changes to natural storage and drainage capacity through encroachment and conversion of watersheds, floodplains, and wetlands, which themselves have created dramatic changes to the natural hydrology.

Addressing this complex contemporary issue, this paper analyses how the management of water has been shaped by both infrastructure and institutional landscapes, and whether it is fit for purpose in the context of climate vulnerability. A focus on current day crises represents an important conceptual and methodological shift away from framing climate vulnerability as a condition of the future. Indeed, case studies of current crisis and failure provide important insights into the vulnerability of the complex water systems upon which contemporary urbanisation depends, revealing much of how institutions and political processes operate [23]. Focusing on how key actors navigate emerging uncertainties and risk illustrates how these shape vulnerabilities or capacities to adapt. Such an investigation also provides insights into sectoral adaptive capacity and the ways in which individual actors and organisations operate in contested institutional landscapes.

This approach builds on a body of work that characterises urban systems as constituting the interplay of actors, institutions and physical infrastructure. From this perspective the interaction of agency, institutions and physical infrastructure are key determinants of vulnerability [23–25]. Moreover, focusing on current crises as they unfold provides an alternative to the 'predict and act' approaches to assessing climate vulnerability that depend on climate projections of the future. Drawing on the lived experience of recent crises highlights how different actors understand, interpret, anticipate and respond to the types of shocks that are expected to arise with greater intensity and frequency as the climate changes. In focusing on historical and current events, attention is directed towards emerging critical thresholds, and the degree of climate variability that is likely to precipitate critical failures and crisis.

## 2. Theoretical Framework to Urban Climate Vulnerability and Adaptation: Reconciling Agency and Complexity

This paper reframes urban climate vulnerability that builds on established conceptualisations around exposure, sensitivity and adaptive capacity [26] by presenting three key conceptual shifts:

- Moving away from simply place-based approaches to vulnerability to a greater attention to the complex social-ecological-technological systems that characterise both water resources and contemporary urbanisation [24,27].
- Drawing on Adger (2006) [26] and the significance of 'adaptive capacity', attention is directed to the internal working of how organisations and institutions operate in the face of stress and crisis, and on the role of individual actors within such structures and processes.
- Moving away from 'predict and act' approaches to vulnerability, by applying a case study approach to emerging stress and crisis, as a way to assess how current trends and trajectories might be approaching thresholds that are in line with climate projections [27].

### *2.1. Complex Social-Ecological-Technological Systems*

'Complex systems' thinking has influenced discourse in the different fields of water, urbanisation, and climate change. In the case of water, theoretical approaches have increasingly adopted frameworks based on complex social-ecological-technological systems, in which the resources, governance structures and processes as well as the infrastructure for storage and distribution constitute a 'coupled system' [28]. Drawing on the seminal work of Holling (1973) [29] and Gunderson (2000) [30] a systems approach provides a framework for identifying and analysing the linkages and dependencies between constituent elements at different scales, as well as the feedback loops that operate between them. Such a perspective has value for identifying vulnerability that might manifest at any point within systems, or in the linkages and relationships between systems. Conversely building adaptive capacity and resilience is argued to require attention to the ecological conditions of the resource itself [31,32], as well as the technology and infrastructure, and most significantly, the governance structures and processes through which management is performed.

In a similar vein, recent literature on urbanisation has moved away from defining the 'urban' solely according to space and territory. The contemporary urban world depends on complex networks of infrastructure and technology that cross geographical, ecological, and administrative boundaries that are increasingly inter-linked and inter-dependent [33,34]. These networks are created and managed by similarly complex institutional structures and processes, comprising a diverse range of actors and interests. It is through these networks that the pace of contemporary urbanisation becomes possible.

Literature on disruptions and the inherent fragility of urban infrastructure also has implications for our understanding of climate vulnerabilities. Infrastructure networks are always precarious achievements, with an inherent fragility of potentiality to fail due to engineering and physical design, or else the institutional arrangements through which they are managed, operated and maintained [23]. It is through these networks that shocks cascade, and diverse impacts are felt beyond the location of any one specific event [35,36]. In the context of climate-related impacts and natural disasters, infrastructure networks create new fault lines of vulnerability within urban environments.

### 2.2. Institutions

The concept of urban systems has been taken up by the emerging field of urban climate resilience, with systems defined according to ecologies and natural resources, infrastructure and technology; and also the institutions by which they are managed, and the agents engaged in their use [24]. Much of the focus of attention in resource, and more recently, in climate vulnerability and adaptation, has been directed towards the nexus of governance, institutions, organisations and actors [37]. Yet there is also recognition of the need for better understanding of the 'dynamic linkages between levels of governance . . . .and the politics of the construction of scale' (Adger et al., 2005; p. 80) and 'institutional processes such as regulatory structures, property rights and social norms associated with rules in use' (*ibid*; p. 78). This interest in institutional dimensions has tended to focus on rules and organisational structures, and the importance of having policies or strategies in place [38,39].

It has been argued that institutional dimensions remain under researched [40], and how they operate in practice, especially in circumstances under which they are strained, remains a critical gap in current research and literature. One of the challenges that systems level approaches face is the reconciliation of the scale of systems with the influence of agency and the extent to which actors can navigate the space within systems or influence system-scale change.

Climate change adaptation literature emphasises the importance of organisations and institutions to deal with greater degrees of uncertainty and risk, and to operate at multiple scales across ecological as well as administrative boundaries, while reconciling competing social and economic interests. Climate change is presented as a 'wicked' problem [41], complex in nature, creating greater variability and consequently increasing uncertainty and risk. With imperatives to move beyond a 'predict and act' approach to assessing future vulnerabilities and acting in anticipation of these, there are calls for new kinds of organisations, institutions, and decision-making. Much of this work is focused on the most appropriate design characteristics of such institutions, much influenced by the seminal work of Ostrom (2010) [42]. Approaches to institutional design have taken on board concepts grounded in panarchy and resilience, with the 'ability to learn' allowing for better accommodation of changing circumstances. For some, addressing a wicked problem requires clumsy rather than linear policy responses [43] with new forms of politics and governance [44] and governance processes that are multi-scale, poly-centric and participatory [45–48] to better embrace complexity. Much of the theoretical work grounded in poly-centric governance argues the need for shared values and visions, and of learning and building trust [42]. Others discuss the preconditions for polycentric governance strengthening adaptive capacity related to internal power dynamics and collaborative versus competitive relations that also includes no overarching centralised authority [49].

Similar arguments have also permeated the literature on water resource management. Recognition of the multiple values, uses, and users involved with water across broad ecological landscapes has to calls for new approaches that are able to transcend established organisational boundaries between government departments and sectors. Adaptive management represents a paradigm shift in water management [50]; one that is consistent with a global emphasis on Integrated Water Resource Management (IWRM). The success of implementation appears to be mixed, and in many cases has either been stalled or reversed, with reports of internal conflicts between government agencies that have sought to protect their own influence and budgets in the face of encroachment from 'integrated' institutional structures.

Addressing water resource and climate adaptation governance, the need for institutions that 'capture structure, agency and learning dimensions' is increasingly recognised [51]. However, institutional design remains poorly informed by the current practice of institutions and organisations in dealing with emerging climate realities. As such the fundamental question of how such institutions might be changed and re-designed remains largely unanswered.

### 2.3. Actors at the Interface

A critical missing piece in this puzzle of adaptive organisations and institutions lies in how institutions actually perform; not in an idealized version of institutions that is based solely on policies and strategies, organograms, and terms of reference but in how actors within and between institutional structures and processes operate. This requires politically nuanced and actor-oriented perspectives.

Urban infrastructure networks are 'political infrastructures' that create and maintain geographies of power, wealth, and inequality [52]. At the same time, there are possibilities for systemic change through 'creative disruptions' or through the exercise of agency or power [53], leading to alternative urban futures that are transformative rather than resilient, and thus more socially and environmentally just. The outstanding questions are therefore how people navigate these political landscapes, but also how higher scales, both in terms of ecology and infrastructure networks, interact to shape these landscapes. Such arguments draw attention to the interfaces between people and systems. However, much of the current work framed around disruptions in urban systems understandably focuses at the interface of the end-user. This is important but its weakness is in only considering one part of the system and wider social-political landscape. While it addresses political, social, and institutional dimensions; it only sees the surface of the pipes and pumps through which the water flows, is distributed, and accessed.

Actor-oriented approaches aim to unpack the functioning of institutions and organisations, and the ways in which key actors operate within such structures and processes [54,55]. Such a focus shifts attention away from idealised notions of institutional design, to the lived reality of how institutions function. This approach of focusing on actors has a long-established tradition in sociology and anthropology [54], and is used to address some of the fundamental, conceptual challenges of the social sciences. On the one hand, it recognises that much of social life is shaped by social structures (as well as technology and institutions; structures can refer to class, ethnicity, language etc.), while on the other it also recognises that actors, either individually or collectively, are able to reshape social structures (sometimes in quite transformative ways). It is an approach that has been applied to the way in which actors within state bureaucracies navigate the interface between the demands and expectations of their government agencies and those of their public constituents [55].

## 3. Case Study Methodologies

A central method of actor-oriented approaches is to focus on actors at different interfaces in multi-layered situations of conflict, potential change, or crisis [54]. Case studies provide a lens for understanding climate vulnerability through the lived experience of shocks, stresses, and crises; drawing on the worldviews of key actors and how they negotiate actions. Conducted over extended periods of time and based on qualitative interview methods and critical observation, case studies are useful in revealing actors' lived realities—how they understand their world and their own actions, and what outcomes they are trying to achieve. This can be complemented with a critical analysis of the context in which they operate; drawing on political economy and political ecology theory.

### Research Methods

The basis for the research discussed in this paper is an analysis of the internal workings of water management institutions that have to confront the stresses, shocks, and crises associated with climate variability. This approach builds on an established tradition within social sciences that situates actors within complex institutional structures and processes; analysing the ways in which they are constrained versus their ability to navigate and reshape these institutional worlds. Focusing attention on the practice of those responsible for implementing policy reveals how outcomes emerge from negotiation between actors and interests, sometimes in ways that are quite different from what is intended in policy documents [54,55].

The programme of research involved extensive fieldwork conducted over a four year period (2013–2017). Research methods brought together distinctive approaches: (i) an empirical analysis of water availability and performance of key water storage infrastructure across the rainy and dry seasons based on available government statistical data, regular monitoring, and analysis of storage capacity and precipitation of key infrastructure; (ii) a review of policy documents and institutional analysis drawing on the policies, strategies and action plans of state organisations with various responsibilities for water resource management; and (iii) extensive participatory, actor-oriented, qualitative research focusing on key individual actors within sub-national water management state organisations. Integrated analysis sought to identify the ways in which water systems operate, and in particular, the ways in which current stresses and crises are exerting pressures and creating failures within these systems.

The fieldwork included a series of semi-structured interviews and Focus Group Discussions (FGDs) as well as less formal conversations and participant observation with key water management actors in Khon Kaen province. Extensive interviews were carried out with key actors from regional and provincial level water management agencies; including Royal Irrigation Department Khon Kaen Provincial Office and Regional Office 6, Department of Water Resources, Regional Thai Meteorological Department, and Regional Environmental Office 9, and local administrations; Khon Kaen City Municipality, and Phra Lap Sub-district Municipality. An important feature of this actor-oriented approach was the depth and quality of relationships established between the research team and interviewees that allowed regular access and, in turn, created the space for in-depth conversations. Interviews were deliberately open-ended in order to elicit actors' own understanding in their own words. With written consent of all participants, interviews were recorded and analysed in Thai, and then translated into English. Thematic analysis of interviews focused on core areas of understanding from key actors.

## 4. Findings

Water resource management in the Chi-Mun River Basin is facing multi-dimensional challenges [56]. Rapid urbanisation and climate change heighten the pressure on water resources [21,22,57]; however, contemporary water crises can be attributed to governance failures [58]. In this study, water crises, defined as abrupt shifts in social-ecological systems that are perceived as threats to socio-economic values and structures, and that require response under conditions of uncertainties [59–61], are compounded by crises that transcend geographic and functional boundaries [62,63].

The study found that water crises have been triggered by several factors, creating crosscutting governance challenges that are shaped by responses of multiple actors as shown in Figure 1. These factors are related to the complexity and interdependence of social-environment-technology systems making up the water system in the region [64]. The analysis reveals inter-related water crises in the basin set off by complex, cross-scale interactions between different sets of variables: (i) natural and ecological; (ii) technical, technological and infrastructure; (iii) social, institutional and political, and (iv) knowledge and information. Key governance challenges are created and nested within these four main domains.

Actors manage water resources, operate infrastructure, and coordinate across ecological-political-administrative boundaries at multiple scales, yet do so based on incomplete knowledge and unreliable information of social-ecological-technological systems. Actors are also confronted with contesting values of water and competing water objectives. Yet their ability to manoeuvre is constrained by the nature of the technology and infrastructure that they are expected to manage. To illustrate points of fragility and potential failures in greater depth, the following section analyses the water system using the systems approach as outlined in Figure 1 to better understand the complexity of social-ecological-technology systems and the relationships between social-ecological and political-administrative boundaries.

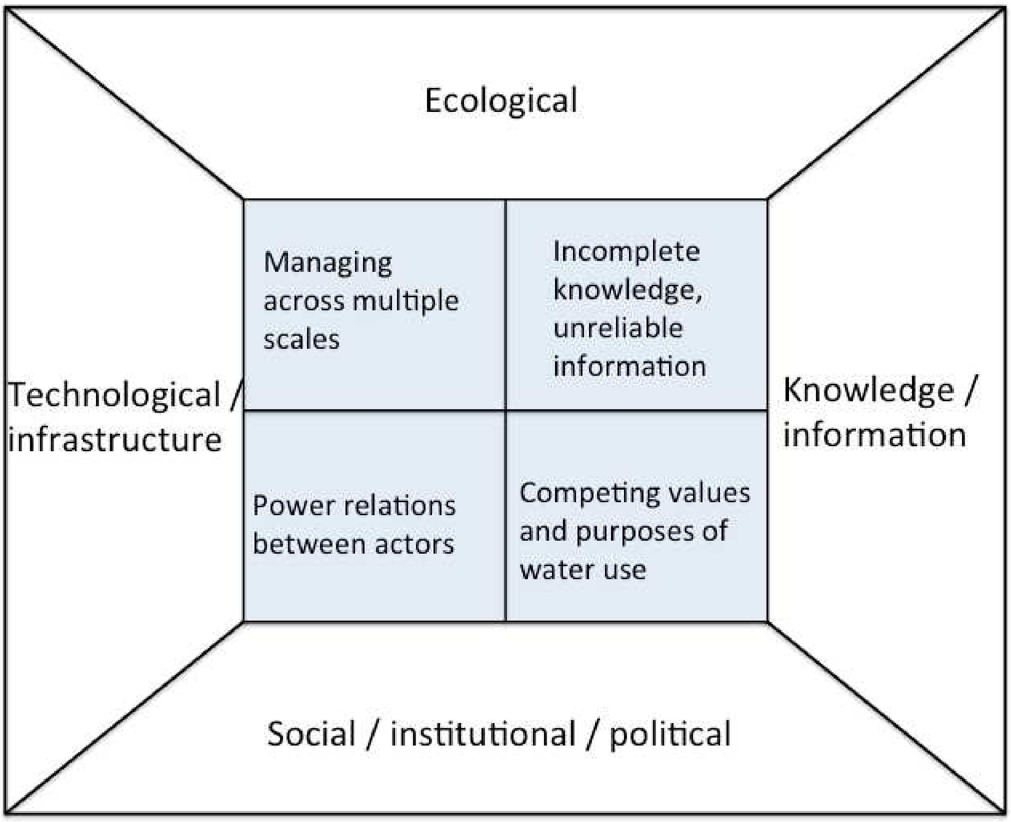


**Figure 1.** Complex interactions of social-ecological-technological systems (outer ring) creating nested cross-cutting governance challenges (inner boxes) for water resource management in the Chi-Mun Basin.

*The Water System: Social-Ecological-Technological Complexity*

- *Ecological dimensions*

Khon Kaen is located in the Korat Plateau, which has two large river systems—the Chi and Mun River Basins (Figure 2). The Chi-Mun River Basin has the largest drainage area into the Mekong River, with combined areas covering 119,000 square kilometres (more than two thirds of Northeast Thailand, covering 15 out of 19 provinces) [65]. The Chi River begins in Chaiyaphum province and drains into the Mun River near Ubon Ratchathani Province.

- *Technological dimensions: the network of water infrastructure*

Khon Kaen depends on a large ecological watershed for its water supply and drainage, supported by a network of large (classified by the Royal Irrigation Department—RID—as water storage capacity above 100 million cubic metres), medium (water storage capacity below 100 million cubic metres) and small-sized (construction period less than 1 year and no land compensation required) dams across the Chi-Mun basin. Water supply for Khon Kaen primarily comes from the Chi River Basin. Here, the Regional Irrigation Office 6 manages a network of water irrigation and infrastructure; including three large-sized dams, 69 medium-sized dams, and 504 electric-powered reservoirs (Figure 2). In Khon Kaen province alone, the provincial RID office manages 14 medium sized, 433 small sized dams, 127 electric-powered water pump stations, and 55 Royal Initiative Projects.

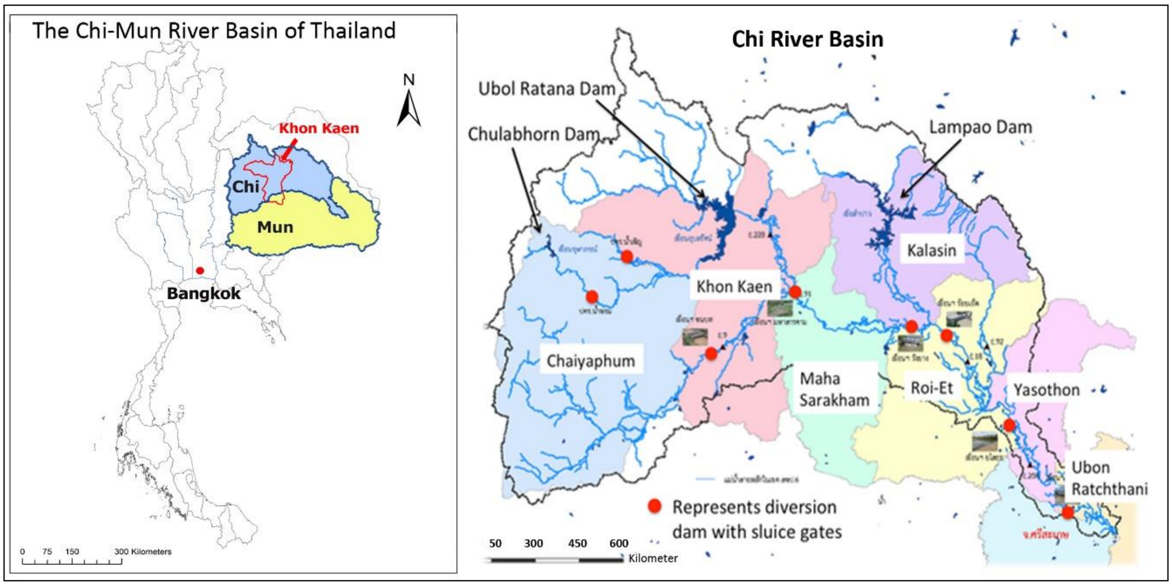


**Figure 2.** Maps of Chi-Mun River Basin and the water infrastructure network in the Chi basin managed by Irrigation Regional Office 6.

- *Institutional structures and power relations*

Such a complex ecological and technological landscape is dependent on equally complex institutional structures: as represented by a range of different government departments and agencies operating at national, provincial, and local levels; each with its own mandate, responsibilities, reporting lines, and financial and technical resources (Figure 3). The institutional structures for water resource management in Thailand have always been highly politicised, and recent changes in the government have brought further changes to an already complex institutional landscape [58,66]. Ultimately, the effectiveness of such an institutional set-up depends on how each of these agencies functions in its own right, as well as how they function together.

There are at least 31 departments and several state enterprises accountable to 10 different ministries involved in the water sector. However, at the national level, four ministries—Interior, Industry, Agriculture and Cooperatives, and Natural Resource and Environment—can be considered the most influential in water resource management. Several departments, including the Royal Irrigation Department (RID), and the Department of Water Resources (DWR), and several state enterprises, such as Electricity Generating Authority of Thailand (EGAT), Provincial Water Works, and Provincial Electricity Authority, operate at the same sub-national level with overlapping responsibility. RID—under the Ministry of Agriculture and Cooperatives—is responsible for irrigation projects, infrastructure construction and maintenance, and provision of irrigated water for agriculture. DWR under the Ministry of Natural Resources and Environment (MONRE) is the core agency in the formulation of policy and Integrated Water Resource Management (IWRM) plans at the river basin scale. Several departments under the Ministry of Interior, such as the Department of Lands, also play a role in influencing water resource management decisions. The Thai Meteorological Department, agency under the Ministry of Digital Economy and Society, serves as the main source of weather information, but has little influence over water management decisions.

There are significant contradictions in these governance structures. For example, there are competing reporting lines between ministries and their departments in Bangkok to the provinces, and within provinces from the Provincial Governor to Sub-District levels. Under the Ministry of Interior, the main administrative bodies with responsibility of local development are under the authority of the Department of Local Administration, while the heads of district and sub-district authorities report to the Department of Provincial Administration under the Provincial Governor. Local responsibilities also often overlap with these competing lines of reporting and accountability.

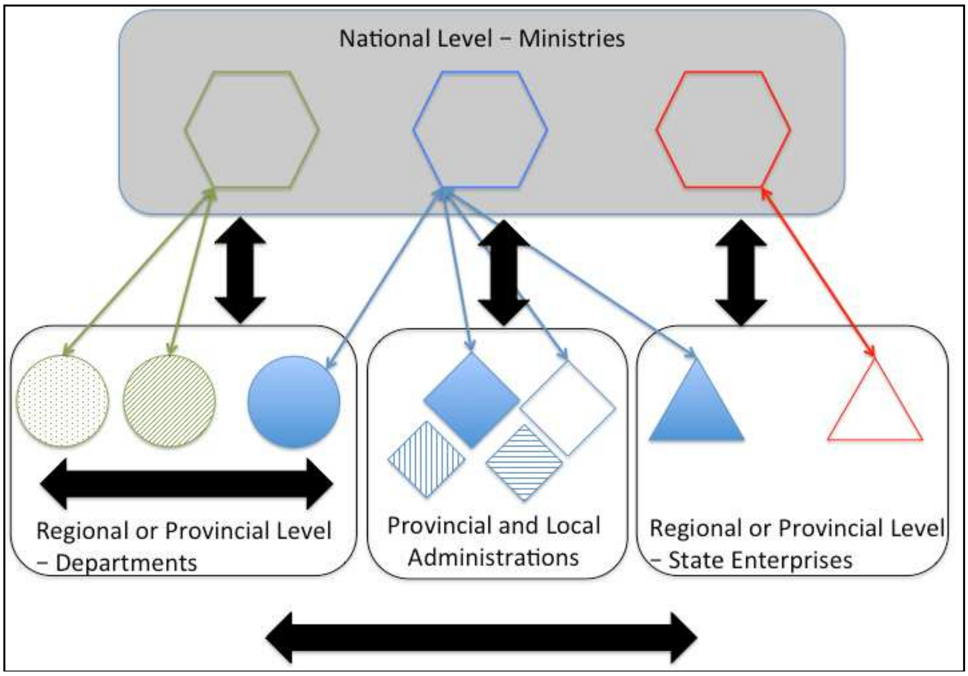


**Figure 3.** Institutional structures of water resource management, vertical and horizontal power relations, and reporting lines of multi-level water actors in Thailand.

At the Chi-Mun basin level, the Royal Irrigation Department (RID) is structured around a mix of basin and provincial organisations, with offices at the regional and provincial levels reporting to the central office in Bangkok. In the Chi-Mun watershed, at least 14 Provincial Irrigation Project Offices under 3 Regional Offices are responsible for the construction, management and operation of dams, reservoirs, and irrigation infrastructure. Regional Irrigation Office 6 is responsible for five Irrigation Projects in five provinces and five Water Supply and Maintenance Projects in four provinces. Each Irrigation Project, headed by a director, is responsible for irrigation and/or diversion dams and reservoirs and irrigated water for agriculture. Similarly, each Water Supply and Maintenance Project is responsible for the construction of irrigation systems and distribution of irrigated water, e.g., Nong Wai is responsible for the irrigation system and water supply of Ubol Ratana Dam. However, Ubol Ratana Dam is managed by the Electricity Generating Authority of Thailand (EGAT), a state enterprise under the Ministry of Energy. Management of dams within the same basin therefore requires coordination across ministries as well as ecological scales, each with its own lines of reporting and coordination. At the basin and provincial level, coordination cuts across departments, sub-national administrative agencies and state agencies; each of which also has its own reporting lines.

At the local level, water shortages and floods are dealt with by strategic plans which are housed in different departments and ministries. RID is a key actor which negotiates between state (provincial governors and/or municipalities) and non-state (rice or fish farmers) actors, as well as navigating institutional power relations with other key actors as EGAT or DWR. These key actors are confronted with contesting values of water between urban residents and farmers, as well as competing water objectives between EGAT and RID. Their ability to manoeuvre is also constrained by incomplete knowledge and information and the nature of the technology and infrastructure that they are expected to manage i.e., management of water due to high rainfall is often the exclusive task of technical experts, with decisions to discharge water from large dams involving little or limited consultation and negotiation with affected stakeholders in downstream areas.

Focus Group Discussions provided insight to a specific example. On 14 November 2016, Ubol Ratana Dam had 2419.36 million cubic meters of water or 99.51% of its total capacity, and the fourteen medium sized reservoirs had a total volume of water of 119.30 million cubic meter or 112.67% of total capacity. Due to unexpected heavy rainfall on 6–9 November, it was necessary to discharge more water from the Ubol Ratana Dam: from 15 million cubic meters per day to 21 million per day for 7 days starting from 17 November. The decision to increase discharge was made on 14 November by the Khon Kaen Water Management Committee. Downstream irrigation projects were informed of the decision though not consulted prior to making the decision. Further monitoring was agreed by the committee, and if rain persisted, additional water would be released (up to 25 million cubic meters per day). The decision to increase water discharge was made despite repeated floods in low-lying areas in Khon Kaen throughout the year (in June, September, October, and again in mid-November).

Changes in institutional structures often take place following crises or disasters [67,68]. This was found to be the case in this study of water management institutions in Thailand. After the 2011 flood crisis, the National Integrated Water Management Office was established in 2012 to address water resources and flood issues; including policies, budgeting and implementation. Chaired by the Prime Minister, and supported by key ministers, the office assumed powers previously held by existing departments and agencies responsible for water resources and floods. In 2014, after the military coup, policies and plans under the National Integrated Water Management Office were abandoned. While the office was removed the National Committee for Policy and Management of Water Resources and Flood Disasters remained. In 2015, a National Water Resources Board (NWRB) was formed, chaired by the Prime Minister to address drought problems as well as provide guidance to the National Committee for Policy and Management of Water Resources and Flood Disasters. NWRB agreed to move the responsibility of the national committee from under the Prime Minister Office to the Department of Water Resources under the Ministry of Natural Resources and Environment.

Although there appears to be a degree of cohesion and coordination at the national level through the National Water Resources Board as an overarching governing institution, the institutional framework remains highly fragmented in practice. Priorities and responsibilities to implement strategies by the assigned agencies often conflict or overlap, resulting in a lack of long-term planning and vision on how to manage water issues in a just, sustainable, and integrated way. Further complicating the picture, there are several influential organisations, and within these several influential individual actors, each with their own interests, knowledge and influence.

A key feature of this complex institutional arrangement is the siloed approach, reflected by individual remits, mandates, and operating procedures; against which organisations are required to report their performance. Such an approach can create efficiency, but it can also create a myopic view, with responsibilities for overall system failure passed down the line. Understanding the roles and responsibilities of the different organisations within this institutional set-up, and how individual agents within these organisations operate, can reveal how well current crises are managed or prevented.

- *Knowledge and Information; generation and access*

The effective functioning of institutional structures is being strained by climate variability. Rainfall is highly variable in both space and time across the Chi basin (Figure 4) and the analysis of precipitation and storage data in this study (Figures 4 and 5) points to water resource management approaching critical thresholds. In the last decade, the Northeast of Thailand has experienced a cycle of severe water shortages in the dry season and flood disasters in the wet season. Low rainfall towards the end of year often leads to water shortages in the following dry season (between November and April) e.g., the dry season that stretched from November 2009 to the end of August 2010 resulted in a water crisis [69]. Again in 2012 and 2013, all districts in Khon Kaen declared a state of emergency due to droughts [70]. The region then experienced its worst water shortages between 2015 and mid 2016 [15,17].

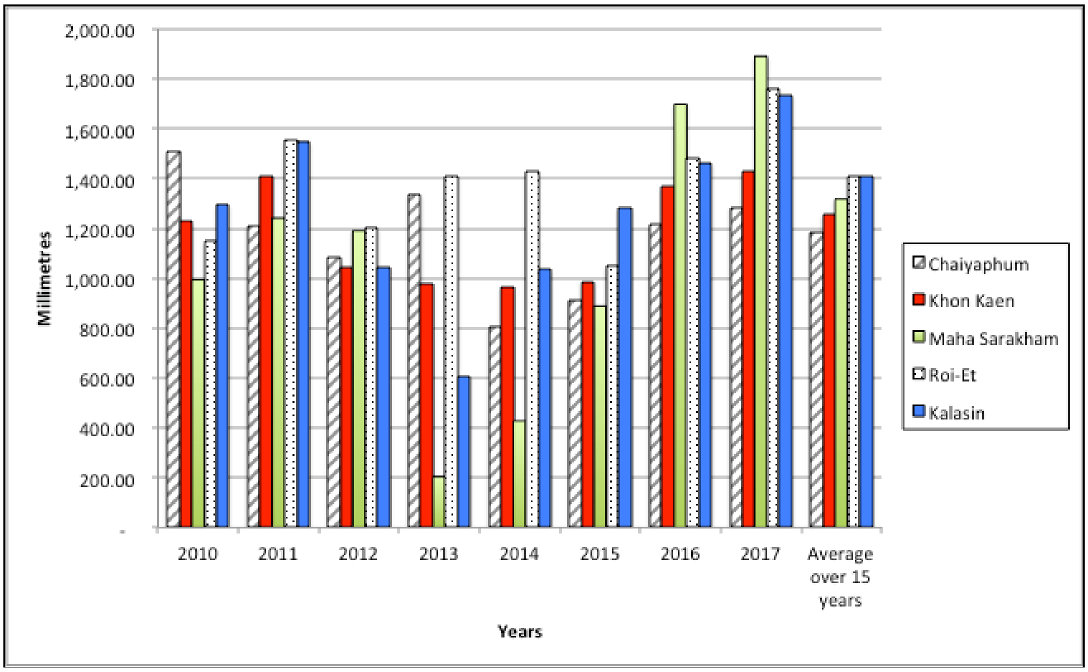


**Figure 4.** Rainfall data for the Chi Basin (Data source: Meteorological and Royal Irrigation Departments).

Reduced rainfall is affecting all the reservoirs of the Chi Basin. The largest reservoir—the Ubol Ratana Dam—faced a serious crisis on the 30 May 2016 with storage at a critical 21.21% of capacity. However in terms of water that can actually be used, this figure represents −3.57% of what is required (pers. comm. Khon Kaen Irrigation Project Office). As alarming as these individual figures are, the full extent of the challenges being faced is evidenced by a series of recent events. Over the last thirteen years, levels in the Ubol Ratana reservoir have gone below dead storage (water in a reservoir that cannot be drained by gravity and has to be kept under normal operating condition [71]) on five occasions, while also coming close to dead storage on one additional occasion.

Rainfall variability is illustrated by the analysis of accumulated water inflow data. Annual water levels in Ubol Ratana Dam from accumulation of water inflow over twelve months compared with average water levels over 48 years are indicative of wet and dry years (Figure 5). High water levels corresponding with reports of severe floods in 2010, 2011, 2017 and water levels below average indicate severe water shortages in 2012, 2014, and 2015 in the Northeast of Thailand. Data also indicates a shifting of seasons (Figure 6) and that water shortages occur when there is an extension of the dry season and floods happen when rainfall continues towards the end of the year. For instance, high rainfall towards end of year in 2010, 2011, 2016 and 2017 led to floods in Khon Kaen [72–74]. What is clear is that there are significant institutional and political challenges for dealing with current variability and future uncertainties in water availability.

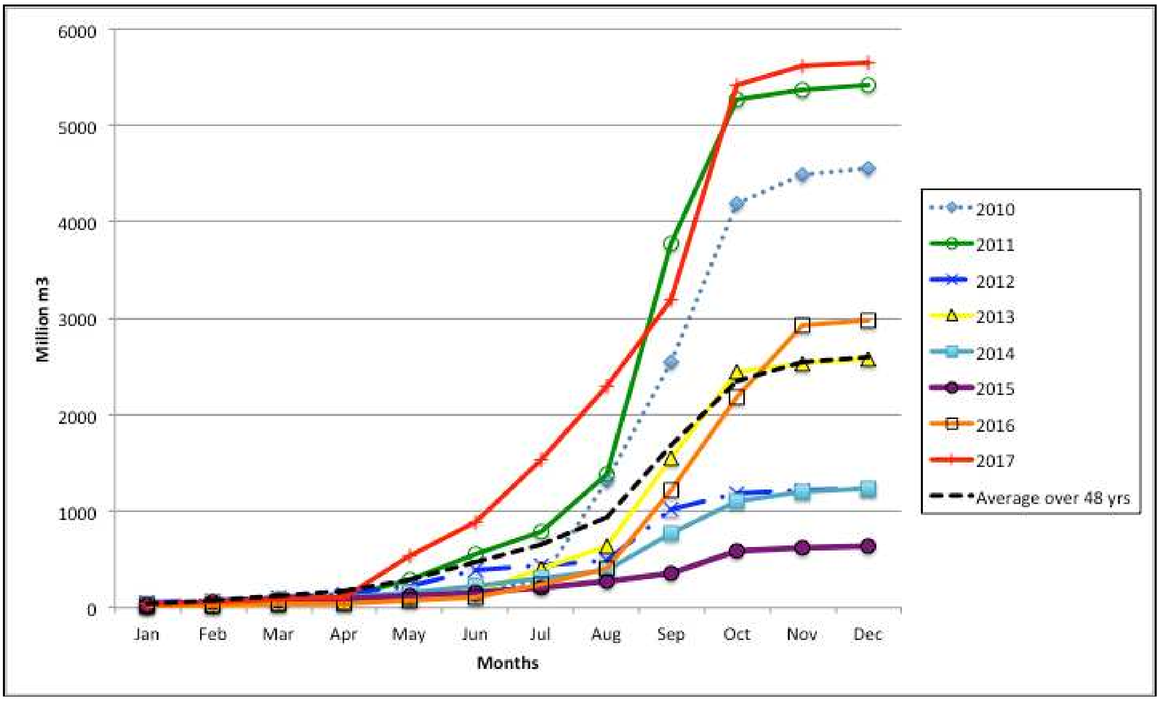


**Figure 5.** Annual water levels and accumulated inflow at Ubol Ratana Dam (Data source: National Hydro informatics and Climate Data Centre).

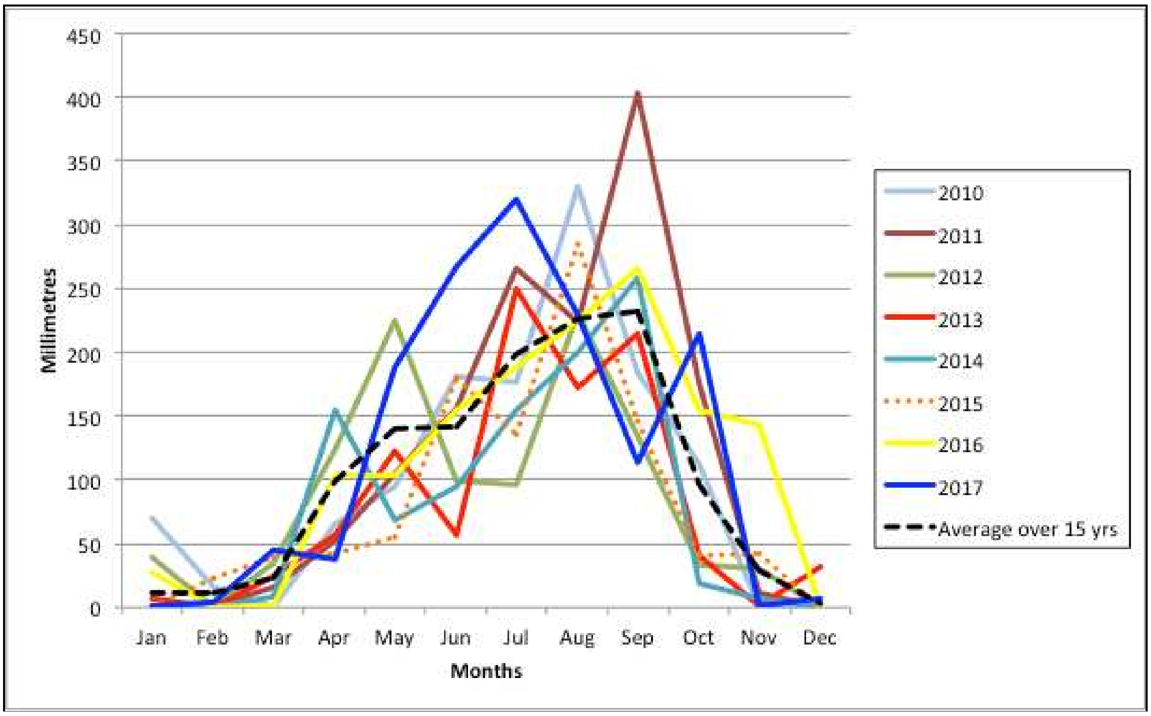


**Figure 6.** Rainfall data of Khon Kaen Province (Data source: Meteorological and Royal Irrigation Departments).

## 5. Discussion—The Interface of Actors and Infrastructure

The ways in which these complex systems of infrastructure operate are clearly influenced by degrees of agency, with actors negotiating and manoeuvering to influence decisions and outcomes. Knowledge, and the ability to act upon insights and information, is also critical for dealing with uncertainty. In some ways, having a water system based on such a range of infrastructure could be seen as increasing resilience to disturbances and shocks if such diversity adds to a degree of diversity, redundancy and modularity [24]; that is to say, if the failure of one reservoir can be offset by the capacity of the other reservoirs. However, in the case of Khon Kaen and the Chi basin, each reservoir provides a different set of services to a different set of users, and the analysis of management responses to current variability demonstrated that the failure of one cannot necessarily be offset by another. Most importantly, management of these reservoirs is shaped by different sets of interests.

An historical perspective is also helpful to the analysis. Each of these reservoirs was built several decades ago, designed for earlier demands and uses, and for a different climate regime. This leads to fundamental challenges for dealing with the uncertainty and variability of emerging patterns of precipitation. Furthermore, the number of weather stations, and their locations, is inadequate to measure precipitation across the landscape. This means that changing patterns of rainfall and distribution may not be detected, and reservoir storage measures might not match with actual water inflow into dams. The purpose of the dams has also changed over time. These irrigation reservoirs were built for a single purpose, provision of water in the dry season for cropping during an era in which the local economy was largely based around rice cultivation. This picture is now changing significantly with a shift from single-purpose to multi-purpose irrigation infrastructure, increasing the complexity of competing operating policies.

The degree to which existing water management is able to adapt to emerging variability was revealed through an analysis of how information is accessed and interpreted, and the extent to which such information is applied. A critical area is in relation to how reservoir rule curves are able to account for, and adapt to, change. Each dam has its own rule curves, which guide the responsible RID provincial office in monitoring and maintaining water at target levels. However, rule curves dictate and influence decisions on when to discharge water or restrict water supply, but do not indicate the quantity of discharged water. Furthermore, monitoring and maintaining water at target levels following rule curves, particularly in the rainy season or during critical period, are done on a day-to-day basis, with discharge amounts determined by daily inflow data and the weather forecast provided by the Meteorology Department. Rule curves are adjusted by the RID central office in Bangkok every 5 years, but can be adjusted after major flood or drought incidents (a reactive response to previous crises). Adding another layer of institutional complexity, some large-scale dams are under the responsibility of EGAT whose responsibility is the generation of electricity. Their water level requirements might not be consistent with flood or drought mitigation measures.

Weather forecasts are provided by the Meteorology Department for a 10-day time-frame. In addition to rule curves and meteorological information, Khon Kaen provincial office also uses historical data of water inflows (monthly average water inflow and monthly accumulated water inflow over 39 years) to monitor and guide decision for maintaining water levels. To change the quantity of water discharged, the decision can only be made from Bangkok, informed by a meeting of key stakeholders and actors; such as EGAT, mayors of municipalities and/or Sub-district Administration Organisation (TAO); to negotiate how much water will be increased, and to inform areas that will be at risk of flooding.

*Institutional Knowledge—Dealing with Uncertainties and Risk*

While the extent to which institutional structures and processes are fit for purpose is a persistent feature of climate literature [75,76], there has been less attention to the internal workings of institutions, or to the ways in which specific actors perceive the world in which they are operating. A central feature of this research was on the internal workings of actors within organizations with a responsibility for water management, and particularly how they interpret what constitutes a 'problem' and thus possible solutions. In this case, it was found that different agencies and actors had their own agendas, interests, values, and beliefs with different interpretations of the nature of the problem (and indeed, whether it constitutes a 'problem').

Within the government institutional structure, different agencies have their own technical areas of expertise and sources of knowledge. Information is not always consistent across different agencies e.g., the Department of Meteorology monitors a wide range of variables that is intended to provide information to assist the RID in projecting water supply for the coming year. In addition, the RID has its own sources of data and information, based on projections for demand (derived from other actors) and agreements on water supply. At a sub-national level, RID monitors the condition of reservoirs across their geographical territory. At the central level, RID in Bangkok provides short-term recommendations to all 17 Regional Irrigation Offices across the country.

Interviews with key actors in these key agencies revealed a mix of confidence in the ability to forecast weather conditions, and in the ability of existing plans to accommodate future variability. What is particularly surprising is that throughout interviews with local actors there was no mention of 'climate change' or the patterns of El Nino and La Nina. Management approaches are seemingly shaped by optimistic interpretations of forecasting, and a sense of hoping for the best, rather than any clear strategic planning. Crisis management has been ad hoc, through implementation of essential emergency responses, as the following quotes reveal.

> *"In June 2016, the RID was hopeful that rain would start in July and believed that it would be a good year for rain based on forecast from the Meteorology Department."*

> *"In November 2016, the RID was relieved dams and reservoirs were full; it would be less stressful to manage water in the summer of 2017 than in the last dry season, and management plans would be followed through."*

> *"If the rain didn't come in July or there was less rain than forecast, the plan would have been to continue to ban farming but with greater enforcement and tighter control."*

However, this level of confidence runs counter to recent experience, including the acknowledgement that serious disaster has only been narrowly avoided, with the costs being disproportionately felt by farmers dependent on irrigation. Moreover, it is not clear to what extent water managers' assessment of future trends is based on any systematic analysis of data. Throughout the fieldwork interviews there was very limited discussion of how patterns of precipitation, water availability and demand might also be shaped by wider changes, such as patterns of land use and forest cover (including transitions to large-scale industrial agriculture), or patterns of urbanization and industrialization that will alter water demand, and put additional pressure on water quality.

In balancing different demands and needs of local stakeholders, government agencies have to make what they see as difficult decisions. They clearly feel that they are caught between competing interests that are difficult to reconcile. Essentially this means that 'urban' water consumption is prioritised. Despite rice farmers being important local stakeholders, in times of water shortage the management response has consistently been to deny water for irrigation. Water managers recognise that these measures have impacted rice farmers and there is clear sympathy for the farmers' plight. However, options are limited to attempts to improve localised storage in small reservoirs and ponds and the effectiveness of such efforts is not clear to decision-makers, and is not evaluated.

In the rainy season of 2016, facing the prospect of a further crisis of water availability in the subsequent dry season, local officials were confident that the needs of domestic water users would be met; however the challenge remained how to meet the needs of rice farmers, as the following quote reveals:

> *"Both the RID and the government think that there will be a water crisis in the next dry season. Actually I think that there won't be any crisis in meeting domestic water and consumption needs. But there will just be a crisis for dry season agriculture. Which leads us to think how we are going to bring water into the reservoir to meet the needs of the dry season farmers."*

The scientific expertise of meteorology and hydrology, supported by a series of modelling tools is highly influential in informing the overall analysis of the problem. However, this expertise is informed by rather limited and sporadic data. Moreover, some key actors and organisations have their own models and data that are designed for their own specific needs and it is not clear how this diversity of information is pulled together for a comprehensive, holistic analysis.

There appears to be a high degree of dependence on historical data (rainfall data of 15 years and accumulated water inflow over 39 years) and assessment of historical trends with the assumption that the current years of crisis are 'unusual' and that these trends will reassert themselves in the near future. As an example, the water level in Ubol Ratana Dam was at 21% of its full capacity in June 2016 (515 million cubic meters), with demand at 581 million cubic meters. According to projected demand it was anticipated that by July there would be only 430 million cubic meters of water remaining. Faced by a major disaster, local state actors were stoical and quietly optimistic; confident in the data they had received, irrespective of global threats from climate change or El Nino/La Nina.

*"Data from the Meteorology Department or from forecasts show that rain this year will be good. That means that in 2017 farmers will be able to plant their crops—definitely. They'll be smiling for sure. They'll be able to do the second irrigated crop if the rain continues to fall and flows into the reservoir from July to November. That means we should be ok—much more than this year."*

Where wider changes are identified and acknowledged there is no sense that there is any need for fundamental change in how water is managed. Indeed, unusual patterns of precipitation across the seasons, merely appears to reinforce the reliance on historical data.

*"There are lot of changes, such as shifting of rainy season. Normally there should not be any storms until September or October. This year, two storms already came in July. There was 60% of water in reservoirs before the storms. The water is now at 70–80% capacity, need to discharge water urgently. More rain is expected, as there are several months until the end of the rainy season. It is difficult to forecast and predict, but we have historical data, and if we observe any unusual events and crises, we can deal with them accordingly."*

These excerpts from field interviews and focus group discussions are significant for several reasons. In the face of uncertainties, and despite approaching crises (on the back of previous crises), there is a continued confidence in being able to muddle through. However, there was also an implicit recognition of additional risks; data and projections have not always proven to be accurate in the past and rainfall data does not necessarily equate with water availability in the reservoirs as rainfall patterns are highly localised. Throughout the conversations, it is striking that much of the focus of attention was how to respond to immediate problems, rather than discussion of root causes or of more strategic approaches to address what have now become regular crises. This tendency also hints at the ways in which state organisations operate in practice; reflected by reactive approaches to potential crises rather than forward planning and longer-term strategic actions.

The extent to which existing infrastructure is suitable for changing circumstances and needs does appear as a prominent concern in some quarters with the problem of water management in the Northeast framed as 'inadequate water storage'. More broadly, concerns for the suitability of existing infrastructure also steers action towards new infrastructure-based solutions, most prominently, the long-planned water diversion scheme from the Mekong mainstream.

*"Rainfall distribution and patterns are a problem, not enough water in the dry season, but too much water with extreme rainfall. Because of the landscapes and terrain, building medium to large scale infrastructure for water storage is not possible. Creating more water retention areas is an approach to solve water issues. Water retention areas can be developed in low-lying areas. But elevation is a problem. Water has to be pumped to higher grounds using electricity."*

Water resource management in the Chi-Mun river basin follows a traditional regime that can be described as a 'wait and see' and 'prediction and control' approach [77]. Historically, managing water resources has relied on networked irrigation infrastructure that was designed for a degree of predictability and controllability [78]. The need to manage such networks in an integrated manner across different scales adds to the challenges facing local water managers who generally have a remit for only one component of the network. While uncertainty is an unavoidable characteristic of managing such complex systems, the last few years have witnessed a growing degree of variability in the Chi-Mun; most significantly seasonal variation, shifting rainfall patterns, and year-to-year variability [79]. To a large degree the quality of decisions depends on the ability of water managers to deal effectively with these elements of uncertainty [80,81].

The ways in which water infrastructure networks and the institutions for managing them have been constructed all contribute to additional constraints [48,82–85]. However, what is perhaps most striking about the case of Khon Kaen is the way in which data and information is incomplete and/or inappropriate, and widely held interpretations of current crises seem to purposively downplay what may well be the emergence of a new long-lasting trend, or indeed a critical threshold, in patterns of precipitation and water availability. Similarly, water managers' main focus of attention appears to be steered towards a rather narrow vision of the water systems and the nature of the management challenges that continue to hold to patterns of the past (Table 1) [83,86].

**Table 1.** Examples of uncertainties and sources of uncertainties within the Chi-Mun water system.

| System Components | Uncertainties of System Behaviour | Incomplete Knowledge<br>Unreliable Information |
|---|---|---|
| Natural/ecological | Rainfall patterns and variability in El Nino and La Nina years | Insufficient number and geographical spread of weather stations for rainfall data |
| | Rainfall distribution in upstream and downstream areas | How changing ecological landscapes and land use affect water levels |
| Technical, technological, infrastructure | Cascading effects of increasing interconnected small-, medium- and large-sized reservoirs | Frequency or timing when rule curves should be adjusted |
| | Effects of different flood models or rule curves used by different actors | What hydrological models and climate scenarios should be used |
| Social, institutional, political | Influence of decision makers on ad hoc Joint Management Committee | Environmental and economic impacts of different trade-offs |
| | Responses to farming ban of rice farmers or prohibition of aquaculture | Economic impacts of floods or water restriction on rice or fish farmers |
| | Influence on driving urban and rural development policies | Increasing demand in water and electricity |

Each of the key organisations has its own set of interests and responsibilities that are again interpreted and applied by individuals in the respective organisations. An important consideration is to ensure that actions carried out do not make them liable for any penalties. Focusing attention on two key organisations provides important insights.

The Meteorology Department is an important source of information but appears to have only limited influence (and arguably interest) in how this information is applied. A key consideration appears to be that the information supplied and shared is considered accurate and reliable so as to ensure they are not liable for any penalties. This could be a factor in not applying climate scenarios and projections. On the other hand, the RID's main responsibility is to ensure water supply. A period of drought therefore puts them under considerable pressure. Operating procedures require RID to ensure that priority water supply needs are met at all times, maintaining domestic water supply and maintaining environmental flows from the reservoirs. In times of water shortage, their options are limited, but are still negotiated at the local level.

In areas where basic water supply needs for domestic use cannot be met, the response has been to support local authorities—at Sub-district (Tambon) level—to extract groundwater for their local needs. This is considered a short-term emergency response, with responsibility for action firmly placed by higher levels of Government on the shoulders of local authorities.

While there is a degree of flexibility and adaptability that in some ways fit with resilience theories of governance—of multi-scale, reflexive, adaptive institutions—the research suggests that this is more clearly characterised as a process of managing one crisis to the next, constrained by a challenging institutional context, and a host of competing demands and expectations.

## 6. Conclusions

This paper has argued the importance of focusing attention on current day crises as a means of assessing future climate vulnerability. The experience of Northeast Thailand in dealing with a prolonged period of variability in water availability and competing demands for water use provides an important case study of global significance. These are similar challenges being faced by other parts of the world.

The influence of institutions in shaping vulnerability and in building adaptive capacity is gradually appearing in the global literature [87,88]. Assessments of climate vulnerability have frequently pointed to weak adaptive capacity due to governance failures [89,90]. Such analysis highlights weakness in legislation and institutional processes but has failed to provide an insight into the internal functioning of key organisations, and the lived realities of those actors on the front line of dealing with climate-related impacts.

This research has global significance. Dealing with a crisis is partly a process of negotiation and manoeuvre, with decisions and actions shaped by a range of factors. While the situation is complicated, several lessons have already emerged. Our findings illustrate that water managers are constrained by the interaction of infrastructure that was designed for different times and different needs, and of institutional structures and processes that have emerged through the interplay of often competing organisational remits and agendas. The degree to which existing water management is able to adapt to emerging variability is further constrained by the ways in which information and knowledge is generated, shared and applied.

There is little consideration of long-term futures. With no apparent effort to bring climate change into their decision-making processes, water managers cling to a confidence that normal patterns of precipitation will return, and that existing models of precipitation will be able to guide management decisions. However, there is also a degree of concern that elements of the system are failing with the recognition that the main reservoir is located in the part of the basin that is now experiencing lower rainfall. The history of investment in large-scale infrastructure continues to influence long-term solutions, drawing on decades-old plans to deal with future uncertainties and risks. Yet given the existing institutional context, solutions that only focus on physical infrastructure cannot be expected to address the scale and complexity of the needs of water management in the future. Ambitions for realising polycentric, multi-scalar governance; and institutions that are learning-oriented and adaptive must be grounded in this lived reality of emerging stresses, shocks and crises.

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## References


1. Maxwell, D. Thailand: Breaking the Cycle of Flooding and Drought. Asian Correspondent 2016. Available online: https://asiancorrespondent.com/2016/10/thailand-breaking-cycle-flooding-drought/#8txCc2H1BEEiPj6c.97 (accessed on 23 April 2018).
2. Mirza, M.M.Q. Climate change and extreme weather events: Can developing countries adapt? *Clim. Policy* **2003**, *3*, 233–248. [CrossRef]
3. Arnell, N.W. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Glob. Environ. Chang.* **2004**, *14*, 31–52. [CrossRef]
4. Immerzeel, W.W.; van Beek, L.P.H.; Bierkens, M.F.P. Climate change will affect the Asian water towers. *Science* **2010**, *328*, 1382–1385. [CrossRef] [PubMed]
5. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, D.; Watanabe, S.; Kim, H.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang.* **2013**, *3*, 816–821. [CrossRef]
6. Güneral, B.; Güneral, I.; Liu, Y. Changing global patterns of urban exposure to flood and drought hazards. *Glob. Environ. Chang.* **2015**, *31*, 217–225. [CrossRef]
7. Brown, R.R.; Keath, N.; Wong, T.H.F. Urban water management in cities: Historical, current and future regimes. *Water Sci. Technol.* **2009**, *59*, 847–855. [CrossRef] [PubMed]
8. Sharma, S.K.; Vairavamoorthy, K. Urban water demand management: Prospects and challenges for the developing countries. *Water Environ. J.* **2009**, *23*, 210–218. [CrossRef]
9. Pahl-Wostl, C. Towards sustainability in the water sector—The importance of human actors and processes of social learning. *Aquat. Sci.* **2002**, *64*, 394–411. [CrossRef]
10. Pelling, M.; High, C.; Dearing, J.; Smith, D. Shadow spaces for social learning: A relational understanding of adaptive capacity to climate change within organisations. *Environ. Plan. A* **2008**, *40*, 867–884. [CrossRef]
11. Scolobig, A.; Prior, T.; Schröter, D.; Jörina, J.; Patt, A. Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality. *Int. J. Disaster Risk Reduct.* **2015**, *12*, 202–212. [CrossRef]
12. Glassman, J.; Sneddon, C. Chiang Mai and Khon Kaen as growth poles: Regional industrial development in Thailand and its implications for urban sustainability. *Ann. Am. Acad. Polit. Soc. Sci.* **2003**, *590*, 93–115. [CrossRef]
13. Asian Development Bank. *Strategy and Action Plan for the Greater Mekong Subregion East–West Economic Corridor*; Asian Development Bank: Mandaluyong City, Philippines, 2010.
14. Office of Agriculture Economics 2015. Available online: http://www.oae.go.th/download/use_soilNew/soiNew/landused2556.html (accessed on 23 April 2018).
15. Thaiturapaisan, T. Drought, a Worrying Situation for Thai Agriculture; SCB Economic Intelligence Centre, 9 July 2015. Available online: https://www.scbeic.com/en/rss/product/1413602906700 (accessed on 20 April 2018).
16. Blake, D. Irrigationalism—The Politics and Ideology of Irrigation Development in the Nam Songkhram Basin, Northeast Thailand. Ph.D. Thesis, School of International Development, University of East Anglia, Norwich, UK, November 2012.
17. Thaiturapaisan, T. Thailand's Drought Crisis 2016: Understanding It without the Panic. SCB Economic Intelligence Centre. Available online: https://www.scbeic.com/en/detail/product/2127 (accessed on 24 March 2016).
18. Bangkok Post. Flash Floods hit Khon Kaen, Kalasin. Bangkok Post. Available online: https://www.bangkokpost.com/news/general/1021265/flash-floods-hit-khon-kaen-kalasin (accessed on 27 June 2016).
19. Thai PBS. Khon Kaen Township Flooded. Thai PBS. Available online: http://englishnews.thaipbs.or.th/khon-kaen-township-flooded/ (accessed on 10 November 2016).
20. The Nation. Khon Kaen Farmers Race to Harvest Paddy as Over-Capacity Dam Threatens Flooding. The Nation. Available online: http://www.nationmultimedia.com/detail/national/30300235 (accessed on 18 November 2016).
21. Artlert, K.; Chaleeraktrakoon, C.; Nguyen, V.T.V. Modeling and analysis of rainfall processes in the context of climate change for Mekong, Chi, and Mun River Basins (Thailand). *J. Hydro-Environ. Res.* **2013**, *7*, 2–17. [CrossRef]
22. Thilakarathne, M.; Sridhar, V. Characterization of future drought conditions in the Lower Mekong River Basin. *Weather Clim. Extrem.* **2017**, *17*, 47–58. [CrossRef]

23. Graham, S. (Ed.) *Disrupted Cities: When Infrastructure Fails*; Routledge: New York, NY, USA; London, UK, 2010.
24. Tyler, S.; Moench, M. A framework for urban climate resilience. *Clim. Dev.* **2012**, *4*, 311–326. [CrossRef]
25. Da Silva, J.; Kernaghan, S.; Luque, A. A system approach to meeting the challenges of urban climate change. *Int. J. Urban Sustain. Dev.* **2012**, *4*, 125–145. [CrossRef]
26. Adger, W.N. Vulnerability. *Glob. Environ. Chang.* **2006**, *16*, 268–281. [CrossRef]
27. Friend, R.; Jarvie, J.; Reed, O.S.; Sutarto, R.; Thinphanga, P.; Toan, C.V. Mainstreaming urban climate resilience into policy and planning; reflections from Asia. *Urban Clim.* **2014**, *7*, 6–19. [CrossRef]
28. Anderies, J.; Janssen, M.; Ostrom, E. A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecol. Soc.* **2004**, *9*, 18. [CrossRef]
29. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
30. Gunderson, L.H. Ecological resilience—In theory and application. *Annu. Rev. Ecol. Syst.* **2000**, *31*, 425–439. [CrossRef]
31. Holling, C.S. Understanding the complexity of economic, ecological and social systems. *Ecosystems* **2001**, *4*, 390–405. [CrossRef]
32. Folke, C.; Carpenter, S.; Walker, B.; Scheffer, M.; Elmqvist, T.; Gunderson, L.; Holling, C.S. Regime Shifts, Resilience and Biodiversity in Ecosystem Management. Annual Review of Ecology, Evolution, and Systematics 2004. Available online: https://doi.org/10.1146/annurev.ecolsys.35.021103.105711 (accessed on 13 April 2018).
33. Graham, S.; Marvin, S. *Splintering Urbanism*; Routledge: London, UK, 2001.
34. Bai, X.; Surveyer, A.; Elmqvist, T.; Gatzweiler, F.W.; Güneralp, B.; Parnell, S.; Prieur-Richard, A.H.; Shrivastava, P.; Siri, J.G.; Stafford-Smith, M.; Toussaint, J.P. Defining and advancing a systems approach for sustainable cities. *Curr. Opin. Environ. Sustain.* **2016**, *23*, 69–78. [CrossRef]
35. Helbing, D. Globally networked risks and how to respond. *Nature* **2013**, *497*, 51–59. [CrossRef] [PubMed]
36. Little, R.G. Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures. *J. Urban Technol.* **2002**, *9*, 109–123. [CrossRef]
37. Adger, W.N.; Arnell, N.W.; Tompkins, E.L. Successful adaptation to climate change across scales. *Glob. Environ. Chang.* **2005**, *15*, 77–86. [CrossRef]
38. Huntjens, P.; Lebel, L.; Pahl-Wostl, C.; Camkin, J.; Schulze, R.; Kranz, N. Institutional design propositions for the governance of adaptation to climate change in the water sector. *Glob. Environ. Chang.* **2012**, *22*, 67–81. [CrossRef]
39. Sondershaus, F.; Moss, T. Your resilience is my vulnerability: 'Rules in use' in a local water conflict. *Soc. Sci.* **2014**, *3*, 172–192. [CrossRef]
40. Galaz, V. Social-ecological resilience and social conflict: Institutions and strategic adaptation in Swedish water management. *Ambio* **2005**, *34*, 567–572. [CrossRef] [PubMed]
41. Rayner, S. Uncomfortable knowledge: The social construction of ignorance in science and environmental policy discourses. *Econ. Soc.* **2012**, *41*, 107–125. [CrossRef]
42. Ostrom, E. Beyond markets and states: Polycentric governance of complex economic systems. *Am. Econ. Rev.* **2010**, *100*, 641–672. [CrossRef]
43. Verweij, M.; Douglas, M.; Ellis, R.; Engel, C.; Hendriks, F.; Lohmann, S.; Ney, S.; Rayner, S.; Thompson, M. Clumsy solutions for a complex world: The case of climate change. *Public Adm.* **2006**, *84*, 817–843. [CrossRef]
44. Giddens, A. *The Politics of Climate Change*; Polity Press: Cambridge, UK; Malden, MA, USA, 2009.
45. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action*; Cambridge University Press: New York, NY, USA, 1990.
46. Leach, M.; Scoones, I.; Wynne, B. (Eds.) *Science and Citizens; Globalisation and the Challenge of Engagement*; Zed Books: London, UK; New York, NY, USA, 2005.
47. Galez, V.; Crona, B.; Osterblom, H.; Olsson, P.; Folke, C. Polycentric systems and interacting planetary boundaries—Emerging governance of climate change-ocean acidification-marine biodiversity. *Ecol. Econ.* **2012**, *81*, 21–32. [CrossRef]
48. Lebel, L.; Garden, P.; Imamura, M. The politics of scale, position, and place in the governance of water resources in the Mekong region. *Ecol. Soc.* **2005**, *10*, 18. [CrossRef]

49. Da Silveira, A.R.; Richards, K.S. The link between polycentrism and adaptive capacity in river basin governance systems: Insights from the River Rhine and the Zhujian (Pearl River) basin. *Ann. Assoc. Am. Geogr.* **2013**, *103*, 319–329. [CrossRef]
50. Pahl-Wostl, C. The importance of social learning in restoring the multifunctionality of rivers and floodplains. *Ecol. Soc.* **2006**, *11*, 10. [CrossRef]
51. Huntjens, P.; Pahl-Wostl, C.; Rihoux, B.; Schlüter, M.; Flachner, Z.; Neto, S.; Koskova, R.; Dickens, C.; Kiti, N.I. Adaptive Water Management and Policy Learning in a Changing Climate: A Formal Comparative Analysis of Eight Water Management Regimes in Europe, Africa and Asia. *Environ. Policy Gov.* **2011**, *21*, 145–163. [CrossRef]
52. McFarlane, C. The comparative city: Knowledge, learning, urbanism. *Int. J. Urban Reg. Res.* **2010**, *34*, 725–742. [CrossRef]
53. Scott, A.J.; Storper, M. The nature of cities: The scope and limits of urban theory. *Int. J. Urban Reg. Res.* **2014**, *39*, 1–15. [CrossRef]
54. Long, N.; Long, A. *Battlefields of Knowledge: The Interlocking of Theory and Practice in Social Research and Development*; Routledge: London, UK, 1992.
55. Lipsky, M. *Street-Level Bureaucracy, 30th Ann. Ed.: Dilemmas of the Individual in Public Service*; Russell Sage Foundation: New York, NY, USA, 2010.
56. Molle, F.; Floch, P. Megaprojects and social and environmental changes: The case of the Thai "water grids". *Ambio* **2008**, *37*, 199–204. [CrossRef]
57. Floch, P.; Molle, F. *Water Traps: The Elusive Quest for Water Storage in the Chi-Mun Basin, Thailand*; Working Paper. Mekong Program on Water, Environment and Resilience (M-POWER); University of Natural Resources and Applied Life Sciences, Institut de Recherche pour le Développement: Chiang Mai, Thailand, 2009.
58. Sneddon, C. Water conflicts and river basins: The contradictions of comanagement and scale in Northeast Thailand. *Soc. Nat. Resour.* **2002**, *15*, 725–741. [CrossRef]
59. Galaz, V.; Moberg, F.; Olsson, E.K.; Paglia, E.; Parker, C. Institutional and political leadership dimensions of cascading ecological crises. *Public Adm.* **2011**, *89*, 361–380. [CrossRef]
60. Homer-Dixon, T.; Walker, B.; Biggs, R.; Crepin, A.S.; Folke, C.; Lambin, E.F.; Peterson, G.D.; Rockstrom, J.; Scheffer, M.; Steffen, W.; et al. Synchronous failure: The emerging causal architecture of global crisis. *Ecol. Soc.* **2015**, *20*, 6. [CrossRef]
61. Taylor, P.L.; Sonnenfeld, D.A. Water Crises and Institutions: Inventing and Reinventing Governance in an Era of Uncertainty. *Soc. Nat. Resour.* **2017**, *30*, 395–403. [CrossRef]
62. Rosenthal, U.; Boin, A.R.; Comfort, L.K. (Eds.) *Managing Crisis: Threats, Dilemmas, Opportunities*; Charles Thomas Publisher Ltd: Springfield, IL, USA, 2001.
63. Sirivasan, V.; Lambin, E.F.; Gorelick, S.M.; Thompson, B.H.; Rozelle, S. The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resour. Res.* **2012**, *48*, W10516. [CrossRef]
64. Pahl-Wostl, C. The implications of complexity for integrated resources management. *Environ. Model. Softw.* **2007**, *22*, 561–569. [CrossRef]
65. Hydro and Agro Informatics Institute (HAII). National Hydroinformatics and Climate (Thaiwater) 2012 Chi and Mun River Basins. Available online: http://www.thaiwater.net/web/index.php/knowledge/128-hydro-and-weather/663-25basinreports.html (accessed on 12 April 2018).
66. Molle, F.; Floch, P.; Promphakping, B.; Blake, D.J.H. The 'greening of Isaan': Politics, ideology and irrigation development in the northeast of Thailand. In *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*; Molle, F., Foran, T., Kakonen, M., Eds.; Earthscan: London, UK, 2009; pp. 253–282.
67. Birkman, J.; Buckle, P.; Jaeger, J.; Pelling, M.; Setiadi, N.; Garschagen, M.; Fernando, N.; Kropp, J. Extreme events and disasters: A window of opportunity for change? Analysis of organizational, institutional and political changes, formal and informal responses after mega-disasters. *Nat. Hazards* **2008**, *55*, 637–655. [CrossRef]
68. Pelling, M. *Adaptation to Climate Change: From Resilience to Transformation*; Routledge: London, UK; New York, NY, USA, 2011.
69. Garbero, A.; Muttarak, R. Impacts of 2010 droughts and floods on community welfare in rural Thailand: Differential effects of village education attainment. *Ecol. Soc.* **2013**, *18*, 27. [CrossRef]

70. Hydro and Agro Informatics Institute (HAII). Available online: http://www.thaiwater.net/v3/archive (accessed on 23 April 2018).
71. Sujarit, S.; The Use of Dead Storage in Term of Dam Safety Aspect. Smart Water Operation Centre 2016. Available online: http://water.rid.go.th/damsafety/document/2559/The%20article%20PDF/4.Dead%20Storage.pdf (accessed on 23 April 2018).
72. Thaiwater.net. Available online: http://www.thaiwater.net/current/floodNE_oct53.html,http://www.thaiwater.net/current/2016/RAI2016/rai_sep2016.html (accessed on 18 April 2018).
73. Khaosod News. Available online: https://www.khaosod.co.th/around-thailand/news_570930 (accessed on 24 April 2018).
74. Thai PBS. Available online: http://englishnews.thaipbs.or.th/khon-kaen-township-flooded/ (accessed on 24 April 2018).
75. Engle, N.; Lemos, M.C. Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. *Glob. Environ. Chang.* **2010**, *20*, 4–13. [CrossRef]
76. Anguelovski, I.; Carmin, J.A. Something borrowed, everything new: Innovation and institutionalization in urban climate governance. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 1–7. [CrossRef]
77. Pahl-Wostl, C. Transitions towards adaptive management of water facing climate and global change. *Water Resour. Manag.* **2007**, *21*, 49–62. [CrossRef]
78. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Stationarity is dead: Whither water management? *Science* **2008**, *319*, 573–574. [CrossRef] [PubMed]
79. Walker, W.E.; Harremoes, P.; Rotman, J.; Van Der Sluijs, J.P.; Van Asselt, M.B.A.; Janssen, P.; Krayer Von Krauss, M.P. Defining uncertainty, a conceptual basis for uncertainty management in model-based decision support. *Integr. Assess.* **2003**, *4*, 5–17. [CrossRef]
80. Pahl-Wostl, C.; Sendzimir, J.; Jeffrey, P.; Aerts, J.; Berkamp, G.; Cross, K. Managing change toward adaptive water management through social learning. *Ecol. Soc.* **2007**, *12*, 30. [CrossRef]
81. Ascough, J.C., II; Maier, H.R.; Ravalico, J.K.; Strudley, M.W. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. *Ecol. Model.* **2008**, *219*, 383–399. [CrossRef]
82. Dewulf, A.; Craps, M.; Bouwen, R.; Taillieu, T.; Pahl-Wostl, C. Integrated management of natural resources: Dealing with ambiguous issues, multiple actors and diverging frames. *Water Sci. Technol.* **2005**, *52*, 115–124. [CrossRef] [PubMed]
83. Brugnach, M.; Dewulf, A.; Pahl-Wostl, C.; Taillieu, T. Toward a relational concept of uncertaintiy: About knowing too little, knowing too differently, and accepting not to know. *Ecol. Soc.* **2008**, *13*, 30. [CrossRef]
84. Lebel, L.; Manuta, J.B.; Garden, P. Institutional traps and vulnerability to changes in climate and flood regimes in Thailand. *Reg. Environ. Chang.* **2011**, *11*, 45–58. [CrossRef]
85. Pahl-Wostl, C.; Lebel, L.; Knieper, C.; Nikitina, E. From apply panaceas to mastering complexity: Toward adaptive water governance in river basins. *Environ. Sci. Policy* **2012**, *23*, 24–34. [CrossRef]
86. Floch, P.; Molle, F. *Marshalling Water Resources: A Chronology of Irrigation Development in the Chi-Mun River Basin, Northeast Thailand*; M-POWER Working Paper MP-2007-02; Chiang Mai University, Unit for Social and Environmental Research: Chiang Mai, Thailand, 2007; 57p.
87. Folke, C.; Carpenter, S.; Elmqvist, T.; Gunderson, L.; Holling, C.S.; Walker, B. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. *Ambio* **2002**, *31*, 437–440. [CrossRef] [PubMed]
88. Berkes, F.; Colding, J.; Folke, C. (Eds.) *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*; Cambridge University Press: Cambridge, UK, 2003.
89. Olsson, P.; Gunderson, L.H.; Carpenter, S.R.; Ryan, P.; Lebel, L.; Folke, C.; Holling, C.S. Shooting the rapids: Navigating transitions to adaptive governance of social-ecological systems. *Ecol. Soc.* **2006**, *11*, 18. [CrossRef]
90. Yusuf, A.A.; Francisco, H. Climate Change Vulnerability Mapping for Southeast Asia. 2009. Available online: https://www.idrc.ca/sites/default/files/sp/Documents%20EN/climate-change-vulnerability-mapping-sa.pdf (accessed on 15 April 2018).