Institutional Management for Infrastructure Resilience

by

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ABSTRACT

To improve the resilience of complex, interdependent infrastructures, we need to better understand the institutions that manage infrastructures and the work that they do. This research demonstrates that a key aspect of infrastructure resilience is the adequate institutional management of infrastructures. This research analyzes the institutional dimension of infrastructure resilience using sociotechnical systems theory and, further, investigates the critical role of institutions for infrastructure resilience using a thorough analysis of water and energy systems in Arizona.

Infrastructure is not static, but dynamic. Institutions play a significant role in designing, building, maintaining, and upgrading dynamic infrastructures. Institutions create the appearance of infrastructure stability while dynamically changing infrastructures over time, which is resilience work. The resilience work of different institutions and organizations sustains, recovers, adapts, reconfigures, and transforms the physical structure on short, medium, and long temporal scales.

To better understand and analyze the dynamics of sociotechnical infrastructure resilience, this research examines several case studies. The first is the social and institutional arrangements for the allocation of resources from Hoover Dam. This research uses an institutional analysis framework and draws on the institutional landscape of water and energy systems in Arizona. In particular, this research illustrates how institutions contribute to differing resilience work at temporal scales while fabricating three types of institutional threads: lateral, vertical, and longitudinal threads.

This research also highlights the importance of institutional interdependence as a critical challenge for improving infrastructure resilience. Institutional changes in one system can disrupt other systems' performance. The research examines this through case studies that explore how changes to water governance impact the energy system in Arizona. Groundwater regulations affect the operation of thermoelectric power plants which withdraw groundwater for cooling. Generation turbines, droughts, and water governance are all intertwined via institutions in Arizona.

This research, finally, expands and applies the interdependence perspective to a case study of forest management in Arizona. In a nutshell, the perilous combination of chronic droughts and the engineering resilience perspective jeopardizes urban water and energy systems. Wildfires caused by dense forests have legitimized an institutional transition, from thickening forests to thinning trees in Arizona.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement and Theoretical Contributions

The usual engineering approach to the resilience of infrastructure—understood as a physical, engineered, and technological systems—defines resilience in terms of the ability of an infrastructure to return (or be returned) to its original state after being exposed to a particular class of risks. A key shortcoming of this approach is that it assumes the original state of the infrastructure to be a static feature of the physical, engineered, and technological systems that make up the infrastructure. This assumption is always false. After any infrastructure is built, it changes dynamically over time. Some of these changes are physical: the infrastructure material degrades or the physical systems in which it is embedded alter, e.g., due to climatic or other environmental changes. Equally importantly, other changes result from human intervention. Operational and management decisions impact the state of an infrastructure at any given moment in time. Degraded systems are repaired, replaced, upgraded, or left in place. Parts of the infrastructure may be improved, adapted, transformed, or removed. And the human-built environment around the infrastructure evolves. All of these changes result from individual and institutional choices about how to manage the infrastructure and its surroundings. And all of these changes also have the potential to significantly impact how the infrastructure behaves during and after a disaster. Resilience cannot simply be understood as *a problem of how infrastructures behave after a disaster*; it must also be understood as *a problem of* *how people and institutions behave before a disaster*. This dissertation examines one important facet of the latter aspect of resilience, which will be defined as *the resilience work of institutions*: the work that institutions do to design, build, operate, maintain, adapt, and transform infrastructures over time that impacts the performance of those infrastructures during a disaster.

Consider a dam on a river. Although the infrastructure seems static, it isn't. The amount of water held behind the dam at any moment of time is managed dynamically, in order to avoid flooding, with water being released from the dam periodically, or withdrawn from the reservoir, in order to create new capacity to absorb future water flows, as well as to provide water for the services that the dam provides, such as irrigation, flood control, or hydroelectric power. The infrastructure physically degrades over time and must therefore be carefully monitored, maintained, and repaired over time, in order to maintain its performance and prevent catastrophic failures. Moreover, the dam's social and ecological environment changes over time, e.g., a town built below the dam might grow significantly or alter its policies for building within the river's floodplain, changing the parameters under which water may be released from the reservoir, or the patterns of rainfall shift due to climate change, in either case necessitating adaptation of the infrastructure (e.g., the building of Roosevelt Dam on the Salt River higher in the 1980s, after devastating floods in Phoenix) or the construction of a new pipe, lower in the reservoir behind Hoover Dam, to feed water to Las Vegas from Lake Mead. Sometimes the whole value proposition for the infrastructure changes and society decides, e.g., to remove the dam and to do something different entirely. 72 dams were removed, for example, in the US in 2016.

To address these deficiencies in making decisions for infrastructural resilience management, this dissertation offers a new model of infrastructure resilience that has three key adjustments.

a. This research defines infrastructures not as physical-engineered-technological systems but rather as sociotechnical systems, with a particular emphasis on the institutions that manage infrastructures. This idea can be applied to any infrastructure, and it encompasses a wide array of potential institutions. Take roads. Roads involve numerous institutions that support their construction and management, such as government budgets, markets for materials, construction companies, urban planning, legal regimes, such as eminent domain, the education, training, and licensing of workforces, gas stations, road signs, traffic signals, administrative traffic regulations, and so on. Without these institutions, roads cannot be designed, built, and provide spaces for traffic service in society (Chapter 2).

b. This research redefines resilience not as bouncing back but rather as a complex combination of dynamics and achievements on multiple timescales, including: (1) the short-term achievement of stability, meaning that flooding on the river is significantly reduced through the proper operation and maintenance of the dam; (2) the medium-term achievement of adaptation to new conditions, e.g., altering the dams operational rules and even physical characteristics in response to changes in streamflow patterns; and (3) the long-term achievement of transformation of infrastructures to meet new societal goals and objectives. Lack of resilience occurs when institutions are unable to achieve these outcomes in relation to the infrastructure. This definition makes clear that resilience is not homogeneous, but rather the multi-faceted outcome of institutions' processes of reasoning about what kinds of risks to worry about and respond to, on what kinds of timescales. Towards this end, some scholars in systems engineering have argued for focusing on systems processes—sensing (monitoring), anticipating, adapting, and learning—as key elements in improving infrastructure resilience (Hollnagel 2011; Park et al. 2013). Each of these processes, however, must be institutionalized in infrastructure-related organizations. Institutional analysis, thus, is indispensable to the analysis of resilience (Chapter 3).

c. This research highlights and emphasizes the resilience work of institutions, including the work of developing and deploying knowledge about the infrastructure (e.g., dams and roads) and its performance vis-à-vis various anticipated risks, as well as the work of opening, maintaining, repairing, adapting, and transforming institutions, as it is critical to the performance of resilience. This work determines how systems perform under different kinds of shocks and the means through which the institution achieves resilience or not. The resilience features of infrastructures are the results of the ongoing institutionalization of epistemological conception, regulation, knowledge, and explicit/tacit protocols at any given time. Given *human intentionality* of institutions in society (Holling, 2001), infrastructures, in response to disturbances ranging from normal stressors to uncertain challenges, must rely on decision making, behavioral adaptations, and organizational coordination for resilience expressed and coordinated through institutional dynamics (Chapter 4).

1.2 Chapter Descriptions

This dissertation begins with a set of theoretical explorations of the resilience of sociotechnical systems (Chapter 2, 3, and 4). The rest of the dissertation (Chapter 5, 6, 7, 8, and 9) then applies the resulting insights to analyze different case studies of the water-energy nexus in Arizona.

Chapter 2 introduces the concepts of systems theory, sociotechnical systems, and institutions. This chapter illustrates the theoretical development of systems theory and sociotechnical systems theory through which the resilience of infrastructures will be articulated in the following chapters.

Chapter 3 connects this sociotechnical concept to resilience. Chapter 3's main contribution is that it argues for a new definition of resilience based on the sociotechnical approach to infrastructure dynamics. Particularly, Chapter 3 explains the key role of institutions with respect to this redefinition.

Chapter 4 proposes a topological framework that explains the types of resilience work by institutions within scales. Resilience work at different temporal and spatial scales, with different organizations, goals, and uncertainties is the main focus of this chapter. Chapter 4 also highlights the institutional interdependencies of infrastructures. By institutional interdependency, the dissertation means the linking of multiple infrastructures through social, economic, or institutional relationships. In 2011, for example, a major tsunami decimated manufacturing in Japan and caused extensive weakness in US markets. This vulnerability resulted not from physical or technological interdependencies but because of supply chain arrangements that linked the two economies (Nanto et al., 2011). Institutional interdependencies are frequently a property of infrastructures and significant contributors to infrastructure vulnerability or resilience. Therefore, the analysis of interdependencies should be incorporated into the analyses of infrastructure resilience.

Chapter 5 applies the sociotechnical systems theory to a particular case study: the way that the allocation of water and hydroelectricity from Hoover Dam have been constituted, regulated, and operationalized by social and institutional arrangements. In particular, this chapter examines the institutional dynamics of resource allocation (e.g., reservoir water and hydroelectricity) through a lens of common pool resource management of Hoover Dam, describing how the utilities and purposes of a technical infrastructure are defined and sustainably adapted or transformed in social backgrounds and within institutional arrangements.

To better understand and analyze institutional interdependence, Chapter 6 focuses on water availability issues and the management of Arizona's water-energy nexus in response to water scarcity challenges. Chapter 6 describes the current landscape of water and energy systems and organizations (e.g., the history of SRP) in Arizona and unbundles the complex structure of institutional threads (e.g., lateral, vertical, and longitudinal threads) of interdependencies in infrastructures. Chapter 6 illustrates how water and energy systems have integrated the physical and institutional infrastructures to supply water and electricity to the city of Phoenix. Institutions work to control water fluctuations, regulate groundwater consumption, and initiate federal level canal construction and water allocation which aims for the resilience of water and energy systems in Arizona.

Chapter 7 investigates the interdependencies of water and energy systems. This chapter focuses on institutional interdependence and interactions between two different systems rather than engineering interdependencies. For instance, the impact of ‘shortage declaration’ in Colorado River allocation impacts both the management of water supply systems and the management of thermoelectric power plants which use diverse sources of water (e.g., Colorado River water, surface water, and underground stored water) for cooling in Arizona.

Chapter 8 examines risk politics of water and energy systems detailed from the perspective of *risk innovation* by Andrew D. Maynard (Maynard, 2015). In this Chapter, the diverse threats (e.g., socio-eco-technical threats) to communities’ values and cultures will be examined in relation to the resilience of infrastructures. In this Chapter, infrastructure resilience is reinterpreted and explained from the point of view of the risk politics of values and cultures embedded in different constituencies (Mary Douglas's grid-grip analysis).

Chapter 9 applies the analysis framework and other institutional analyses done in the previous chapters to 'forest management' in Arizona. Chapter 9 investigates the institutional transition from 'thickening' forests due to fire suppression to managed 'thinning' of those forests to enhance their resilience to wildfire, and the implications of that for water and energy systems and functions in Arizona. In brief, the institutional analysis of infrastructure resilience extends to the socio-eco-technical contexts of Arizona.

Finally, Chapter 10 concludes with a summary of this research, policy suggestions, and plans for future research.

CHAPTER 2

INFRASTRUCTURE AS SOCIOTECHNICAL SYSTEMS

2.1 Introduction

Chapter 2 will first introduce systems theory in order to focus on the concept of the development and function of infrastructure as not only technological and material but also as outcomes of human institutional dynamics that change in response to social influences. The initial shape of technology was relatively simple; however, since the advent of the Industrial Revolution to the present, the rapid increase of human populations has been affecting the design of technological systems in society. As technological systems grow in scale and complexity, a new approach in operating and managing these complicated infrastructures is needed. Therefore, massive and highly interdependent technological systems should emphasize frequent and tight interactions between social and technical components. In this context, a new concept of the socio-technological system has been accentuated (Werfs & Baxter, 2013). The socio-technological system perspective is perceived of as essential in examining a complicated system by considering the tight interdependence and interactions between a society and a technological system. As such, infrastructures cannot be resilient without being properly operated, managed, and planned by human organizations and institutions. Operation, management and planning are usually based on particular norms and rules called institutions or social infrastructures (Anderies et al., 2004). In a sociotechnical system, maintaining a resilient system frequently means a proper operation, management and planning of a system by several appropriate institutions. In other words, infrastructure is a sociotechnical complex system governed by human institutions and organizational decision making.

2.2 Systems Theory

This research analyzes infrastructures using a systems approach to show the characteristics of infrastructures as dynamic and open, sociotechnical systems. By definition, a system is "any entity, conceptual or physical, which consists of interdependent parts" (Ackoff, 1969, p.332). Thus, a systems approach is, here, defined as a holistic method for considering the interdependence of components to assess systems-level problems or phenomena. This follows Bertalanffy's ideas, which focus on the complex interdependence of independent components and the feedbacks that occur among them. This contrasts with more static approaches that focus on organization as 'closed systems' (Trist, 1978) and the engineering performance of individual infrastructures or components. Instead, Bertalanffy's approaches to "feedbacks" and "open systems" examines what happens when dynamic components and their failures interact with other components. "Feedbacks, in man-made machines as well as in organisms, are based upon structural arrangements" (Bertalanffy, 1950, p. 28) in which the behavior of each part influences the behavior of other parts, thus rendering them interdependent and "a system." Open systems are dependent on the exchange of components which enter and come out of them while "maintaining themselves in exchange of materials with environment, and in continuous building up and breaking down of their components" (Bertalnanffy, 1950).

> The theory of development and of life in general must be a ‘system theory’—that is no more to be doubted or disputed. The question only remains what relation there is between this ‘system theory’ and physics. (…) We have also seen that the chemical and physico-chemical theories, Goldschmidt’s theory, crystal analogy, Gestalt theory, cannot yield a complete explanation of development. There remains, therefore, for the present state of investigation at least, only one possibility: that of an ‘organismic’ theory, using specific biological concepts. (Bertalanffy, 1933 translated by Woodger, pp.180-181).

In contrast to Descartes’ reductionism, Bertalanffy’s systems view emphasizes the Aristotelian viewpoint: “The whole is more than the sum of its parts” (Bertalanffy, 1972, p.407). Accordingly, modern technology, including infrastructure, should be conceived of as a system and necessitates a holistic analysis on the **dynamic** performance of a system rather than a reductionist analysis (Bertalnaffy, 1972, p.420). The Tavistock Institute in the UK expanded the systemic dynamics of Bertalanffy’s systems theory to include social and institutional components in the 1960s (Mumford, 2006), labeling the resulting system an open, sociotechnical system.

Granted the importance of system analysis there remains the important question of whether an enterprise should be construed as a ‘closed’ or an ‘open system’, i.e. relatively ‘closed’ or ‘open’ with respect to its external environment (Emery & Trist, 1960, p. 84). The technological component has been found to play a key mediating role and hence it follows that the open system concept must be referred to the socio-technical system, not simply to the social system of an enterprise (Emery & Trist, 1960, p.86). Considering enterprises as ‘open socio-technical systems’ helps to provide a more realistic picture of how they are both influenced by and able to act back on their environment (Emery & Trist, 1960, p.94). **Open systems** “may spontaneously re-organize towards states of greater heterogeneity and complexity, and that they achieve a ‘steady state’ at a level where they can still do work (Trist, 1978, p.45). Organizations governing sociotechnical systems should remain open to society for transparency and accountability.

The conception of sociotechnical systems was created and circulated for “the joint optimization of the social and technical systems” while studying the relationship between technological performance, economic production, and mining industries (Mumford, 2006, p.321; Bertalanffy, 1950; Emery & Trist, 1960). Building on Bertalanffy’s systems theory, Thomas Hughes also used a sociotechnical systems approach to analyze large infrastructure developments (Hughes, 1983, p. 5; Bertalanffy, 1933; 1950; 1968; 1972). “Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping” (Hughes, 1987, p. 51). Hughes argued that sociotechnical systems evolve following a pattern of phases—invention, development, innovation, technology transfer, growth, competition, consolidation, momentum—on their way to becoming ‘large technological systems’ (LTS). According to Hughes, the evolution of technologies such as large-scale infrastructures is not just an engineering problem-solving process, but a systematic and complex co-evolution of social and technical arrangements and dynamics including diverse institutions (e.g., regulations) and participants (e.g., firms, utilities and investors). (Hughes, 1983; 1987; see also Pinch & Bijker, 1984). Viewed from this perspective, infrastructure can be understood in terms of the "complex interactions between humans, machines and the environmental aspects of the work system" (Baxter & Sommerville, 2011, p. 5).

2.3 The Diversified Applications of Systems Theory and Sociotechnical Systems

Systems theory has widely affected the conceptualization of sociotechnical systems. Social science and engineering field such as modern organization theory (Elinor Ostrom and others), Social Studies of Science and Technology (STS) (Bruno Latour and Langdon Winner), infrastructure as common pool resources (Frischmann, 2012), safety engineering (Erik Hollnagel and others), and sociotechnical infrastructure systems (Rolf W. Künneke), all of which congruently describe infrastructures as dynamic, open, sociotechnical systems. The next sections will evaluate how diverse scholarship has developed from the initial sociotechnical systems theory and evolved with other areas while contributing the conceptualization of sociotechnical systems as dynamic, open, and complex systems.

2.3.1 Modern organizational theory and Hughes' large technical systems

Hughes' sociotechnical systems approach is basically rooted in Bertalanffy's general systems theory (Hughes, 1983, p.5; Bertalanffy, 1933). As Hughes (1983) stated, Bertalanffy's work crucially affected his system conception and systems thinking for the development of the electricity system. Usually in this study, "system" refers to a technical system, such as an electric transmission system. Sometimes the reference is, as noted, to a system with interacting components, some of which are not technical (Hughes, 1983, p.6).

> Hughes' notion of 'open system' is in accordance with the foundation of modern organizational theory, which is focused on the interactions between organizations and environments. Before the introduction of 'open system,' social scientists emphasized the conception of 'closed system,' and made efforts to define the characteristics of 'organization itself' (Emery & Trist, 1960, p.84).

> In practice the system theorists in social science (and these include such key anthropologists as Radcliffe-Brown) refused to recognise these implications but instead, by the same token, did "tend to focus on the statics of social structure and to neglect the study of structural change" (Emery & Trist, 1960, p.84)

As Emery & Trist (1960) stated, before the conception of 'open system' was widely accepted, social scientists focused on how organizations are formalized and what determinants differentiate organizations from institutions rather than what makes organizations changes and how environments affect organizational structures and cultures. Thus, before the introduction of the 'open system' conception, old institutionalism focused on the 'internal structure' and ignored the 'external environment' (Trist, 1978, p.44).

Since the introduction of old institutionalism's distinction between institutions and organizations, organizations are regarded as a loose and unstable structure with a limited technical competence, but as organizations go through the process of 'institutionalization,' institutionalized organizations "take on a special character and to achieve a distinctive competence or, perhaps, a trained or built-in incapacity" (Selznick, 1996, p.271). According to Selznick (1996), institutions have "orderly, stable, socially integrating patterns." New institutionalists view institutions as 'rules, norms, and equilibria' which govern and intervene in human interactions and performances in organizations (Crawford & Ostrom, 1995).

In particular, new institutionalists investigate how environments interact with organizations and how social institutions control human behaviors in organizations. Furthermore, 'new institutionalists,' who focus on the bounded rationality of individuals, argue that collective action cannot be reduced to individual behaviors (Selznick, 1996). This notion crucially affected the further development of sociotechnical systems and shared common ground with systems thinking theory. Their notion that "[the] properties of supraindividual units of analysis… cannot be reduced to aggregations or direct consequences of individuals' attributes or motives" (DiMaggio & Powell, 1991, p.8) resonate with the idea of complex systems thinking and sociotechnical systems as dynamic and open systems. In contrast to Descartes' engineering reductionism, the sociotechnical systems approach inheriting new institutionalism is congruent with Aristotelian systems thinking.

2.3.2 Bruno Latour’s hybridized network and the modernity paradox of infrastructures

According to Latour (1991), the world is a system of networks. Modern society has struggled with a modernity dilemma of purification which creates two distinct ontological zones dissociating humans from nonhumans (p. 10). They have put the epistemological ‘Great Divide’ between human culture and nonhuman nature as seen in John Wesley Powell’s report, ‘*1878 Report on the Lands of the Arid Region of the United States*’.

> The central assumption of his plan—and it seems to have been Powell’s controlling idea through his entire Washington career—was that the wild rivers of the West had to be mastered. “All the waters of all the arid lands will eventually be taken from their natural channels,” (…) (Worster, 1985, p.134)

However, the more the moderns reject hybrids, which is a mixture and networks of humans and nonhumans, the more they have, through *translation,* quasi-objects or ‘interbreeding’ such as “one continuous chain the chemistry of the upper atmosphere, scientific and industrial strategies, the preoccupations of heads of state, the anxieties of ecologists” (Latour, 1991, p.10) (**Fig. 1**).

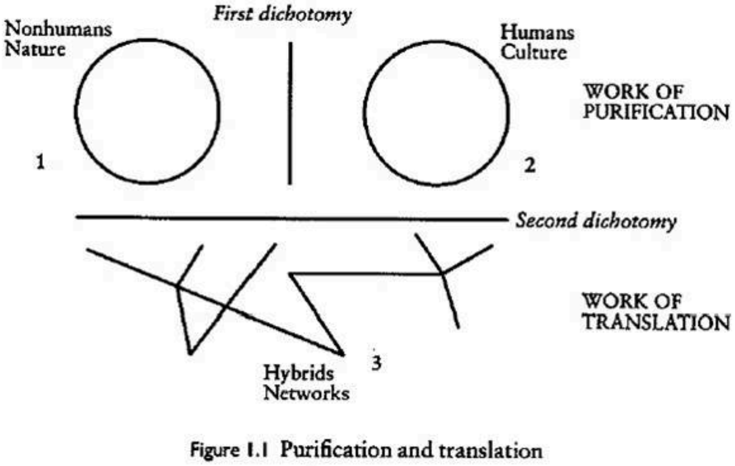

Figure 1. Purification of translation (Latour, 1991)

This is a paradox of modernity. Modern society has no choice but to depend on technologies, and these technologies and social arrangements are more entangled in networks of modern society. Efforts to make a concrete division between human society and nature rely heavily on technologies, which entails more mediation and translation work between human organizations and technological apparatuses.

> What link is there between the work of translation or mediation and that of purification? This is the question on which I should like to shed light. My hypothesis – which remains too crude—is that the second has made the first possible: the more we forbid ourselves to conceive of hybrids, the more possible their interbreeding becomes—such is the paradox of the moderns, which the exceptional situation in which we find ourselves today allows us finally to grasp (Latour, 1991, p.12).

Along these lines, infrastructure as quasi-objects symbolizes Latour's modernity paradox. Moderns have endeavored to protect and sustain its society with both ontological and epistemological division from nature. Infrastructure for modern stability has coped with nature's uncertainties and instability. The 'Great Divide' between society and nature is a result of the investment of financial and 'purified' natural resources into soft (culture, rules, standards, norms, protocols) and hard (dams, roads, railways, electricity grids etc.) infrastructures. More importantly, despite this robust dissociation (or purification), on the other hand, infrastructure should be interconnected for consistent performance as networks. In other words, the infrastructural accomplishment of societal stability is basically based on two characteristics of infrastructure: robust disconnection from nature and tight interconnectedness of networks. Modern infrastructural functionality can be sustained by the dissociation of built environments from nature as Latour (1991) stated. Dikes put boundaries around rivers and separate inhabitants from nature. Modern networks such as infrastructures epitomize the division work of modern science and technology (Latour, 1991; Edwards, 2003). The problem that, as Latour (1991) diagnosed and anticipated, modern society needs additional technologies in order to construct clearer boundaries around society. Engineered hybrids (e.g., dams, dikes, roads, rails, grids, aqueducts, and telecommunication towers) and hybridized management have been more and more intertwined and become more interdependent. We've used infrastructures to face nature and divorce ourselves from its risks, but this has been possible only by thoroughly fashioning interdependent society and technologies. "We have never been modern" with respect to hybridized, open, and complex infrastructure networks.

This paradoxical ‘Great Divide’ matches engineering scholars’ recent diagnoses of modern infrastructure jeopardized by complex networks. Additional proliferation of translation (network society) for interdependent infrastructure needs more back-up plans and redundant resources via complex networks, which exacerbate the vulnerabilities of infrastructure (Rinaldi et al., 2001). This is a well-known network dilemma. However, his analysis has a limitation as a useful tool for resolving the infrastructure dilemma. Despite the great insight on the networks of hybrids, Latour (1991) failed to suggest a realistic governance framework in response to the modern dilemma. Furthermore, Latour’s ‘actant’ concept and its lack of discrimination on both human and nonhuman actants can be conceived of as a disdain for human dignity.

2.3.3 STS, infrastructures, and design politics

In Science and Technology Studies (STS), infrastructure has been interpreted as a heterogeneous, open, and dynamic assemblage of law, history, culture, politics, policy, technology, and science (Star, 1999; Jenssen et al., 2015). Infrastructure is not just a physical or material structure, but a ‘deliberate design’ as seen in Winner’s (1980) analysis. The design of infrastructures, (e.g., the height of the Long Island bridge) is a resultant negotiation of political and social tensions between heterogeneous communities (Winner, 1980). According to Winner (1980; 1993), infrastructure is essentially open to politics and society. Thus, the neutrality of social construction of technologies should be rejected, and instead society must reflect on technopolitics, social inequality, technological ethics, technology and labor unions, and environmental justice regarding infrastructures.

More broadly, to Winner, even the invention of technology is political. For instance, tomato harvesters invented by the University of California replaced handpicking with cost-efficient machines in the agricultural industry. In the 1970s, about 32,000 farmworkers lost their jobs. Later, the creation of tomato harvesters developed into litigation between the University of California and California Rural Legal Assistance. The University of California was charged with the inappropriate consumption of governmental subsidy, which came from taxpayers, for private groups such as agricultural companies at the expense of detrimental impacts on rural communities. The innocuous invention of machines became inherently political in rural areas of California.

> The issues that divide or unite people in society are settled not only in the institutions and practices of politics proper, but also, and less obviously, in tangible arrangements of steel and concrete, wires and transistors, nuts and bolts (Winner, 1980, p.128).

Winner (1980; 1993) criticizes 'social construction' while focusing on social values around the process of production, infusion, consumption, and consolidation of technologies. Winner's contribution to sociotechnical systems theory is to open a space for discussion on how to open, whether to open, who will open, and how to use technologies inside the 'black boxes.' Winner's evaluation on the similarities between technologies and 'legislative acts' (Winner, 1980, p.128) is reminiscent of the conceptions of boundary object such as Star's (1999) infrastructure and Busch's (2011) standards. Consolidated technologies as ‘boundary objects’ appear differently to different groups (Star and Ruhleder, 1996). “[An] infrastructure occurs when local practices are afforded by a larger-scale technology, which can then be used in a natural, ready-to-hand fashion” (Star & Ruhleder, 1996, p.6). To Winner, infrastructures (e.g., bridges), given their convoluted politics and technologies, are not closed, but open, dynamic, and complex systems in society.

The problem with Winner’s assertion is that ‘what are technologies’ cannot be demarcated from ‘what is not’ anymore after technologies became consolidated in a particular fashion of society. Consolidated technologies are not ‘in the black box’ but already compose social contexts. In this sense, Latour’s (1991) networks of quasi-objects and the conceptualized ‘actant’ are more persuasive in that, for the democracy of technoscience, network analysis is necessary rather than technological assessments.

2.3.4 Infrastructure as a Common Pool Resource (CPR) in society

Intrinsically, infrastructures are open venues for allocating common pool resources (e.g., roads for open spaces, dams for water, grids for the transmission of electricity generation from fossil fuels, etc.) (Kunneke & Finger, 2009; Frischmann, 2012). Therefore, social-ecological resilience research, which focuses on knowledge governance for sustainable social-ecological systems, intrinsically includes the management and operation of infrastructure. Common resources from social-ecological systems are allocated and delivered via open, dynamic, and sociotechnical infrastructures. In some sense, how to allocate and deliver common-pool resources is all about how to sustainably share the capacity of infrastructure and allocate the sequential usage of facilities with the management of spatial and temporal divisions on infrastructural usages.

However, despite the potential of the theoretical foundation for institutional analysis, a modern institutional framework shows a lack of consideration of technologies and infrastructures. The traditional social-ecological research on the governance of commons needs more discussion on how technologies (e.g., infrastructure) as common pool resources are socially constructed and distributed for social value (Frischmann, 2012). Investigation on sociotechnical governance is tied to the studies on the governance of common pool resources and should receive more attention from the scholarship of social-ecological resilience. In this sense, the sustainable management of infrastructures sheds lights on Ostrom's idea about common pool resource management.

According to Ostrom, eight conditions for sustainable management of common pool resources can be suggested as follows. (1) Clearly-defined boundaries (effective exclusion of external parties), (2) Congruence between the resource environment and its governance structure or rules, (3) Collective-choice arrangements, (4) Effective monitoring for enforcement of rules, (5) Graduated sanctions for violations, (6) Low-cost and easy-to-access conflict resolution mechanisms, (7) Securing the right of the resource appropriation of self-governing, and (8) Multiple layers of nested enterprises for large common pool resources. Applying these criteria to a specific case, Chapter 5 will delve into a sociotechnical approach to the management of Hoover Dam.

2.3.5 Infrastructures as Sociotechnical Systems

The operational performance of infrastructure systems during both routine and emergency contexts is always a product of the technological and physical components embedded in a procedural matrix of social and organizational management (e.g., operational decision-making, systems maintenance, budgeting, engineering design, and various social rules, politics) (Kunneke & Groenewegen, 2009; Bolton and Foxon, 2011; Larkin, 2013; Jensen & Morita, 2015). Recent scholarship in the field of science and technology studies has expanded on Hughes's and Mumford's early ideas, and this literature describes infrastructure as an assemblage of societal imaginaries, community values, cultural cognition, social practices, legislative rules, standards, and the labor of people (Star, 1999; Slota & Bowker, 2017; Shove, 2016; Miller, 2017). Understood as sociotechnical systems, infrastructures are shaped by social ideologies (who participates), processes (in what ways), and purposes (to what effect) (Miller, 2017; Linnenluecke et al., 2011). For instance, roads provide a stable service space for traffic, but this public service depends on the institutional co-production of ongoing technical adaptations, such as checking traffic volume, the adjustment of traffic light intervals, and even users' compliance to myriad traffic signs and rules (e.g., lanes, green light, speed limit, HOV lane, etc.) (Latour, 1991; Miller & Wyborn, 2018).

In particular, sociotechnical systems entail organizations (communities, social collectives, and informal associations) with institutions and governance rules. Sociotechnical systems are generally designed, built, and operated in multi-institutional contexts where diverse people and organizations generate outcomes and arrange processes of the systems. According to Mumford (2006), an open sociotechnical system concept “considered technical structures and work roles as two systems that were both part of one inclusive system” and offered a foundational basis for understanding the importance of complex interactions between technical systems and social arrangements around it (Mumford, 2006, p.321).

Indeed, systems theory developed into a more sophisticated theory to model the relationship between technical systems (e.g., infrastructures) and social arrangements, namely the concept of a *sociotechnical system* (Emery & Trist, 1960), and this sociotechnical systems approach helps us better understand the dynamics, openness, and complexity of infrastructures. A sociotechnical system integrates both social and technical elements, especially where the interactions and feedback relationships between these elements align system functioning (Hughes 1983; Finger et al. 2005; Baxter & Sommervile, 2011). Sociotechnical systems such as infrastructures (e.g., roads, dams, water pipelines, electricity grids, power plants, etc.) thus necessitate collaborative and complex communication pathways between social and technical components (Geels et al., 2007; Kroes et al., 2006; Werfs & Baxter, 2013), which has given rise in recent years to extensive integration of communication and technological infrastructures in cyberphysical systems (Peter M. Champion et al., 2018).

2.4 Institutions and the management of infrastructure: boundary challenges

Infrastructures are always under pressure because of many natural and social variables that occur outside of their clear boundaries. In other words, infrastructures are open not only to social users (e.g., residents and firms) but also environmental characteristics while holding boundary lines static, which render large infrastructures innately vulnerable (Edwards, 2003).

2.4.1 Sociotechnical management

In terms of social changes, infrastructure as *socio*technical systems should provide stability, which is a sustainable “space of flow” that allows the production, circulation, and application of knowledge, services, and goods to modern society regardless of social fluctuations (Castells, 1996; Edwards, 2003). For instance, roads with institutional lines, signs, signals, and police officers’ tickets transition vacant spaces into transportation conduits, roads. These institutional settings and protocols, which should not be improvisational but persistently facilitate the transportation of people, goods, and knowledge. Roads should be flexible and adaptive to social emergencies and changes. For instance, roads should be flexible, regardless of the original meaning of actants (Latour, 1991), able to allow ambulances or fire trucks to exceed speed limits, ignore traffic signals, and go over road lines with knowledge flexibilities and transitions responding to social uncertainties. Road knowledge systems should have the capacity for managing adaptiveness for traffic fluctuations in the short-term, administrative planning and implementation for re-pavement and new road constructions due to population growth in the mid-term, and the social solidification of transformational transportation systems (e.g., autonomous vehicles) in the long-term.

Regarding environmental disturbances, for instance, open roads are vulnerable to environmental stressors and disturbances such as daily icing and thawing (in winter), monthly heavy rain (in summer), yearly snowstorms and hurricanes (in monsoon seasons), and sea level increase in decades due to climate change. However, in emergencies, intentionally inundating public parks can avoid the flooding of central, urban areas (e.g., Hurricane Katrina) and cutting electricity grids can prevent catastrophic wildfires (e.g., the California state wildfire case in 2018), and the ramping up of sub-pumps and back-up substations instead of main facilities is needed to recover power lines and water supplies as soon as possible. Firemen even use the water from swimming pools to extinguish fires (Woods, 2011). These small cases of knowledge transitions to respond to uncertainties and abnormalities in social and environmental changes are examples of the boundary dilemmas that dynamic, open, sociotechnical infrastructures face.

2.4.2 Institutions and sociotechnical resilience

Institutions are, particularly, enablers which facilitate the transition across stability and adaptiveness of boundary dilemmas and infrastructural dynamics. To be resilient, infrastructure should be stable as well as flexible for resilience via institutions (Beunen, Patterson, & van Assche, 2017). Institutions, as embedded knowledge (Collins, 1993), are accountable for the organizational stability and flexibility which govern infrastructure. Institutions, the expression of patterned human intentionality (e.g., norms, rules, and equilibria) (Crawford & Ostrom, 1995, p.582), govern managerial work of organizations (e.g., governmental departments, corporations, communities). Thus, infrastructure resilience hinges on the stability and flexibility of institutions.

Sociotechnical systems theory rarely accounts for these infrastructural and institutional dynamics.

As such, institutions are crucial components in the resultant resilience of infrastructure. For example, the President's Commission on Critical Infrastructure, established by President Clinton in 1996 (Moteff et al. 2004), included the integral role of institutions in its definition of critical infrastructure:

> [Critical infrastructure is] the framework of interdependent networks and systems comprising identifiable industries**, institutions (including people and procedures)**, and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States … (President's Commission On Critical Infrastructure Protection 1997, Appendix B B-2, emphasis added)

2.4.2.1 The definition of institutions

This research focuses on the set of stipulated rules such as protocols, statutes, policies, and court decisions governing a system as well as internalized incentives and controls, normative values, cultural symbols, and common beliefs. Accordingly, an institution is defined here as an assembly of formal or informal incentives or norms, rules (e.g. stipulated protocols, regulations, and constitution), and cultural, social, political, and economic alignments for governing a system or infrastructure (North 1990; Jentoft et al. 1998; Scott 1995, 2014). In the context of critical infrastructure, we focus on organizations of people and institutions which operate, manage, and reconfigure infrastructure systems.

Thus, they investigate how the institutional rules, norms, and strategies of organizations play a role as a formal or informal structure that governs human interactions and performances in an organization (Coleman 1987; North 1990; Crawford and Ostrom 1995, p.583). They emphasize how "observed regularities in the patterns of human behavior" can "prescribe, permit, or advise actions or outcomes for actors" (Crawford and Ostrom 1995, p.582-583). According to Ostrom (2011), working rules align and justify decision making through constraining, monitoring, and sanctioning human behaviors. Scott (2014), who focuses on sociological institutionalization, also extends the institutional spectrum to cultured cognition as well as norms such as identities, symbols, authority, and obedience, which are broader than Ostrom's (1990) regulative institutions.

2.4.2.2 Key features of institutions

Various disciplines, such as political science, sociology, economics, social-ecology, and robustness analysis have examined institutional governance in organizations and systems. For instance, in the book *Leadership in Administration*, Philip Selznick focused on the distinction between institutions and organizations. Whereas an organization can be characterized as an "expendable tool, a rational instrument engineered to do a job," an institution is regarded as "a responsive, adaptive organism" (Selznick 1957, p.5). For Selznick, while institutions are adaptive and changing, they are driven by a need to secure and stabilize both within and beyond as they confront internal and external pressures.

Largely, two key implications regarding institutions from social science studies can be distilled: (1) institutions function as a set of rules for stabilizing societies, and (2) institutions function as a structured means for orderly adaptation to social and technological change. Both are relevant to the resilience of infrastructure that looks static but changes dynamically.

First, institutions sustain stability, or “structurally induced equilibria” (Knight 1992, p.37). New-institutionalists emphasize how “observed regularities in the patterns of human behavior” can “prescribe, permit, or advise actions or outcomes for actors” (Crawford and Ostrom 1995, p.582-583). According to Ostrom (2011), working rules align and justify decision making through constraining, monitoring, and sanctioning human behaviors. Formal and informal structures for regulating behaviors pave the way for more stable societies than those without such institutions (North, 1990; Selznick, 1996; Scott, 2014).

Second, institutions can also enable the flexibility of an organization that manages infrastructural dynamics. According to Selznick, an institutional or organizational structure is “an adaptive product, responsive to environmental influences” (Selznick 1996, p 274). For Selznick, while being adaptive, institutions nevertheless seek security and persistence as they confront internal and external pressures. Thus, institutions as adaptive but persistent organisms, can be a critical governing structure for the sustainable adaptiveness of infrastructure systems.

2.5. Conclusion

This chapter introduces the sociotechnical concept of infrastructures using systems theory. Systems theory views infrastructures as open, dynamic, and complex systems which are 'jointly optimized' with technical assessments, financing, social and institutional regulations, and constitutional politics. Thus, analyses on social and institutional components as well as the arrangements of infrastructures must be understood as crucial components of infrastructural dynamics including resilience.

Chapter 3 will discuss the relationship between resilience and sociotechnical systems. Critical questions posed in the next chapter include: What is the theoretical background for the emergence of resilience from the perspective of Science and Technology Studies (STS)? Regarding this question, what is the critical issue of the management of infrastructures? What is the contribution of institutions to solve this challenge? How do institutions manage the boundary dilemma of robustness and flexibility of infrastructures? Finally, what are the limitations of sociotechnical systems theory in explaining resilience? These questions will be critically examined in the next chapter.

CHAPTER 3

RETHINKING RESILIENCE AND SOCIOTECHNICAL SYSTEMS

3.1 Introduction

Chapter 2 introduced the idea that infrastructures are, when properly understood, sociotechnical systems. Technological infrastructures are created, maintained, operated, and continually reshaped by the ongoing "activities of human factors" (Geel 2004, p. 900). This implies that the choices that people and organizations make determine how resilient an interdependent infrastructure system will be to a given risk at a given point in time (Rinaldi et al. 2001; Vespignani 2010).

Yet, how to incorporate a plurality of resilience concepts into the framework of sociotechnical systems theory is still a key question in the management of infrastructures. Infrastructures are dynamic, but the management of infrastructure should be stable as well as flexible in society. Stable yet adaptive institutions manage robustness/ stability in the short-term, adaptation in the mid-term, and transformation in the long-term. This chapter develops *a multi-faceted model of resilience as the short-term achievement of stability, the medium-term achievement of adaptation to new conditions, and the long-term transformation of infrastructures to meet new societal goals and objectives*. Chapter 3 also investigates the limitations of sociotechnical systems theory in explaining this redefined resilience.

3.2 Infrastructural Dynamics and the Sociotechnical Systems Theory

From the sociotechnical systems theory perspective, invisible components such as particular configurations of political constituencies, rules, norms, protocols, cultures, and sociotechnical imaginary constitute a complex network of interdependent infrastructure (Larkin, 2013; Jensen et al., 2015). According to Hughes (1983, p.2), “power systems are cultural artifacts.” Given that resilience is the capacity to sustain, adapt, and transform the structure and process of a system to withstand internal and external disturbances, infrastructure resilience should be understood from the question of how institutions (social and cultural aspects of systems) sustain, adapt, and transform the structure and processes of infrastructure.

Sociotechnical systems theory (Emery & Trist, 1960; Hughes, 1983) cast doubt on the old ‘closed system’ theory and paved the new way for ‘open system’ perspectives. Different styles of electricity supply systems in three cities (e.g., Berlin, Chicago, and London) demonstrate differentiated variations in the matrix of social and technical intermingling. According to Hughes (1983), social and cultural aspects (e.g., geographical, cultural, managerial, engineering, and entrepreneurial characters) affected these three regions and the power systems differently developed in each city (p.17). “There was no one best way of supplying electricity” (Hughes, 1983, p.17). The notion of this ‘open system’ perspective has influenced organizational sociology, STS (e.g., Latour’s ANT), High Reliability Organization theory, and further the process approach of resilience engineering for infrastructure resilience.

Moreover, the conception of ‘reverse salient’ (Hughes, 1983), which was hinted at by military strategies and conceptualized as a designation of ‘critical problems’ in developing technical systems, provides a foundational idea to resolve the obduracy problem of infrastructure. Reverse salients play out as barriers in inventing, improving, and consolidating a new technology in society. The conception of ‘reverse salient’ based on systems theory (Bertlanffy, 1933) are not confined to technical issues but expanded into a wide array of problems in socializing technologies. “Reverse salients need not be technical; in fact, the most important reverse salients are often legal, political, social, or cultural” (Edwards et al., 2007). Thus, the institutional reverse salients can be represented with a wide spectrum in every community and can be different based on its culture, administration, and entrepreneurship while contributing to the obduracy of infrastructure (Hommels, 2005).

Given that systems’ adaptation is integral to infrastructural management, the notion of institutional barriers can be a great point to be mediated for infrastructure resilience. Social institutions reify embedded human intentionality in both negative and positive ways that influence individual actions and organizational goals. Hence, understanding the role of institutions as catalytic matters as well as reverse salients is imperative to implementing resilience tasks (sustaining, adapting, and transforming) of infrastructure.

Almost 40 years ago, Hughes (1983) had already pointed out that technological innovation and adaptation cannot be understood as a stand-alone influx, but as systematized settings in a certain way that a society is particularly in favor. This awareness provides a foundational insight for the issues such as interdependence, trade-offs, and obduracy problems associated with infrastructure resilience.

> A systems approach facilitates the use of the reverse salient-critical problems method because reverse salients are observably weak in relationship to other system components, and because, as Edison himself wrote, **the improvement of one component in a system will reverberate throughout the system and cause the need for improvements in other components**, thereby enabling the entire system to fulfill its goal more efficiently or economically (Hughes, 1983, p. 22-23, emphasis added).

The third contribution of sociotechnical systems theory for understanding infrastructural dynamics is a structural framework to comprehend the development of a system. For instance, Hughes' framework helps to understand how the plural variations of systems emerge, develop, and consolidate in different societies. The nature of developmental phases comprises eight settlements. Hughes (1983) identified and ordered the phases for sociotechnical 'pattern of evolution' (e.g., invention, development, innovation, technology transfer, growth, competition, consolidation, and momentum) in the formation, evolution, and standardization of 'large technological systems (LTS).' According to Hughes (1983), the evolution of technologies is not just an *outcome* of engineering problem-solving, but a systematic, complex, and social *process* including diverse social institutions (e.g., regulations) and participators (e.g., firms, utilities, and investors). In particular, the dynamics of developmental phases between infusion, growth, and consolidation illustrate that the infrastructural life-cycle could also be the iterative cycles of stability and adaptability. This reiterative evolution (e.g., developmental changes and consolidation states) of ‘large technological systems’ open a window to understanding infrastructural dynamics, which is helpful to understand infrastructure resilience. However, Hughes’ sociotechnical framework also has not fully explicated the dynamics between infrastructural stability and adaptations. To help understand the challenges of incorporating stability and flexibility into infrastructural management, the next section sheds light on the dichotomy issue and mediation discussions on risk and resilience.

3.3 Risk and Resilience

3.3.1 Quantitative vs. Qualitative

The conventional risk assessment for physical infrastructure resilience (e.g., engineering resilience) is deemed as outdated and a resilience approach (e.g., resilience as a process) to infrastructure is conceived of as more applicable to modern risks given uncertainties. This chapter casts doubt on this dichotomy and seeks a mediation.

Typically, the concept of ‘risk’ has been interpreted as “the possibility/ uncertainty/ chance that the activity will have some undesirable consequences, or the activity itself, that which is often also referred to as a risk source or a threat” (Aven, 2012, p.36). The conventional concept of risk is defined as “a chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor" (EPA). In particular, according to Aven (2012), the concept of 'risk' began to be formalized with "maritime insurance and was used to designate the perils that could compromise a voyage" (Aven, 2012, p.35). Along these lines, the British Medical Association confirms that the English word, 'risk' originates from the Greek word, '*rhiza*,' which means "hazards of sailing too near to the cliffs: contrary winds, turbulent downdraughts, swirling tides" (Aven, 2012, p.35). From this origin, the concept of 'risk' has been developed into a sophisticated quantified insurance framework.

Since the 1970s, however, this quantification-based definition of risk [Risk = Probability of an accident $*$ Consequence in lost money/deaths] has dramatically changed into more qualitative frameworks. Depending on the discipline in question, the definition of risk can vary (e.g., expected value (loss), probability of an (undesirable) event, objective uncertainty, etc.). Notably, the latest definitions of risk include a prominent characteristic, *uncertainty,* which means that the quantification of consequences from actions cannot be predicted or quantifiable. According to newer definitions, risk can be stated as "an uncertain consequence of an event or an activity ($R=C$)". Or, risk can be regarded as "uncertainty about and severity of the consequences (or outcomes) of an activity ($R=C\&U$)". Also, risk can be "the effect of uncertainty on objectives ($R=ISO$)." These definitions are all qualitative and are characterized by the concept of *uncertainty* (Aven, 2012, p.37).

3.3.2 Alternatives to the quantification of risks

Newer definitions of qualitative risks, which entail *uncertainty* and *ambiguity,* led to the emergence of risk governance (Asselt & Renn, 2011). "[M]any risks are not simple and cannot be calculated as a linear function of probability and effects" (Asselt & Renn, 2011, p.436). Asselt & Renn (2011) argue that current 'systemic risks' are complex, uncertain, and ambiguous, and these traits of risks in modern society necessitate a governance framework rather than newer assessments. "Uncertainty, complexity, and ambiguity point to different reasons why many risks defy simple concepts causation" and shed profound light on *risk governance* (Asselt & Renn, 2011, p.438). Given that the results of risk assessments can be divergent depending on 'scale,' 'interactivity,' and 'contingency' (Jasanoff, 1993, p.125), a paradigm shift such as risk governance is a must for risk societies. "One immediate consequence of contingency is that what people claim to know about risk is in fact constructed in different ways in different political and cultural settings" (Jasanoff, 1993, p.127). Political cultures significantly affect the evaluation of risks, which clearly illustrates the ambiguous nature of risks (Asselt & Renn, 2011).

Urlich Beck (1986) also pointed out several issues in technoscience that involve self-manufactured risks as their attributes. It is paradoxical that, in the process of modern methods of controlling risks, risks have been mass-produced in tandem with the advancement of science and technology for resolving pre-modern problems (Beck, 1986). To Beck (1986), modern risks are already incalculable and unlimited. Enhancing social deterrence for technoscience, by recognizing the limitation of technologies (reflexive modernity), is the prerequisite for tackling modern risk problems (Beck, 1986).

Moreover, as Stirling (1999) stated, “the traditional treatment of risk as an objectively determinate quantity” should be “complemented with a sophisticated discussion of the essentially value-laden nature of the assumptions which necessarily frame and inform any analysis of risk” (p.120). Complex risks in society require a paradigm transition from conventional methodologies to an innovative framework such as *risk innovation*, which can scrutinize multi-layered risk landscapes (Beck, 1986; Maynard, 2015). Indeed, the essential governance elements for modern risks are “communication, inclusion, integration, and reflection.” (Asselt & Renn, 2011, p.439).

With this in mind, the effect of efforts above, in trying to escape from the quantification trap of risks, is to foreground the co-production of risks in society. Anticipatory governance is aware of the characteristics of socially embedded risks and aims at the co-evolution of science and society. Anticipatory governance responding to uncertainty, complexity, and ambiguity in modern risks need “an array of feedback mechanisms,” collective imagination, and the engagement of diverse stakeholders (Barben, Fisher, Selin, & Guston, 2008). The features of modern risks such as complexity, uncertainty, ambiguity, the lack of boundaries, incalculability, and the necessity of anticipatory governance have commonalities with the conceptualization of *resilience*. More broadly, a robust feedback loop between science and society (Stewart, 2000) can be regarded as a more salient component for sound decision-making environments for both *risk* and *resilience*.

3.3.3 The emergence of resilience: plural resilience concepts

Accordingly, in resilience scholarship, the complexity, uncertainty, and governance frameworks, instead of “command-and-control strategies” (Folke, 2006, p.255), have been focused on since Holling’s (1973) proposal on ecological resilience. Holling (1973) dismisses the single stable equilibrium notion of the traditional ecology and argued for multi-stable states of *a complex adaptive system*. The traditional ecology was based on Pimm’s (1986) mathematical resilience view. Pimm’s (1986) resilience was based on the singular equilibrium and bouncing back of a system, which emphasizes the return time to the original state as ‘resilience capacity’. Pimm’s resilience is quantifiable and measurable by the amount of time that was taken for a system to return to the previous static original state after a disruption.

3.3.3.1 Engineering resilience

Though the in-depth examinations of institutions as well as infrastructures are essential for the resilience of socio-technical systems, analysis of institutions is rarely carried out in the field of engineering resilience. From the perspective of engineering resilience, according to the US National Science and Technology Council, resilience is defined as a capacity of a specific infrastructure system (or facilities in infrastructure systems) at urban or regional levels to absorb the shocks of extreme events such as natural disasters (McDaniels, 2008)[1]. In other words, the two critical attributes, ability to withstand external shock robustly (robustness) and ability to bounce back rapidly (rapidity), were conceived as the main components of the resilience concept in the engineering resilience field (Chang & Shinozuka, 2004; Holling, 1996; McDaniels, 2008;

MCEER, 2005). Engineering resilience perspective focuses on how to retain or recover the functionality of physical infrastructures to the single equilibrium when exposed to a variety of stressors. Thus, in the engineering resilience approach, robustness and rapidity of infrastructure to the original state are scrutinized (Bruneau, 2003; MCEER, 2005; McDaniels, 2008; Pimm 1986; 1991; Wang and Blackmore, 2009).

Engineering resilience emphasizes efficiency, constancy, and predictability rather than the multiple equilibria view of ecological resilience which underlines persistence, change, and unpredictability. However, in the ecological resilience field, the magnitude of disturbances that a system can absorb and the adaptive capacity toward new equilibria are critical in order to understand resilience capacity (Folke, 2006; Folke et al., 2004; Gunderson, 2000; Holling, 1996; Walker et al., 2004). We can observe lacuna in engineering resilience discourse; that is, even if a system moves to another desirable state in accomplishing alternative *new equilibrium*, the new stable states cannot be deemed as desirable or as the ultimate recovery state of a system. Put simply, engineering resilience perspective can evaluate *new equilibrium* as chronic instability—perennial deficit and less resilience (**Fig. 2**). This point clearly demonstrates why it is not appropriate to postulate a general or single equilibrium (Holling 1996; Scheffer et al., 2001) for the resilience of socio-technical complex network systems supported by human and social interactions. Hence, the engineering resilience concept, which highlights a static state, is not enough to reflect the tight interdependence and interactions between infrastructures and society.

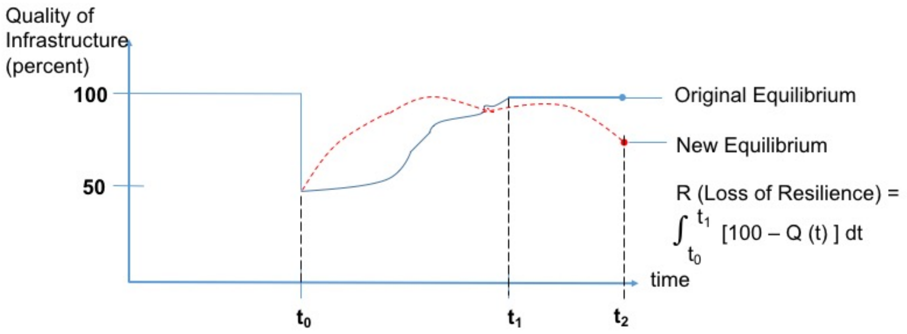

Figure 2. Measuring resilience (modified from MCEER, 2005; Wang et al., 2009)

3.3.3.2 Resilience engineering

Recently, a new way of seeing resilience, or *resilience engineering*, has emerged in the field of engineering; that is, to view resilience as ‘a process’ rather than ‘a product’. This perspective refers to resilience as a quality rather than a quantity and points out not only what makes the system persistent and bounce back but also how the system maintains resilience (Hollnagel, 2011). In particular, Hollnagel (2011) defined resilience as “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain the required operations under both expected and unexpected conditions” (Hollnagel, 2011, p.xxxvi). In this context, the definition of the resilience of a system is stretched to day-to-day system operation and maintenance depending on the protocols of internal systems. Resilience engineering emphasizes system functionality rather than the ability to bounce back to the original state after some disturbances. In other words, how a system can retain its functionality to adapt to diverse exogenous and endogenous variables is more investigated. Put differently, we can say that a system is resilient if the system performs appropriately and is able to interact with its socio-technical environments (Rinaldi et al., 2001). If that is the case, how can a socio-technical system function meet the requirement changes of various societal standards and fluctuations constantly adapting to biophysical conditions? How can a critical infrastructure absorb disturbances and retain its essential functionality to adapt to multiple stable states (Holling, 1973; Folke et al., 2003; 2004; Walker et al., 2004)?

In response to these questions, the people and the institution that operate, manage, and interact with the systems must be taken into account. From the resilience engineering perspective, it is not a bouncing back capacity but the appropriate functionality of a system is more underlined. Therefore, we can inquire into two points in terms of resilience which are worth examining (Hollnagel, 2011; Park et al., 2013). The first is how people in a particular organization are able to monitor the emerging risks and anticipate the possible results with the knowledge acquired by sensing. The second is how people respond to multiple situations with the knowledge system organized by monitoring, anticipating and learning to maintain the knowledge produced, validated and circulated by an iterative process (Clark et al., 2010).

Infrastructure cannot be resilient without being properly operated, managed, and planned by organizations and governing institutions. In a sociotechnical system, retaining functionality means a proper operation, management, and planning of a system with diverse institutions. Graceful extension of the capacity of infrastructures entails institutional extension and adaptation of physical and material systems to prepare for, respond to, and recover from the disturbances within or out of boundary competence

(Woods, 2011; McDaniel, 2013). Thus, examining the resilience of critical infrastructure demands an investigation into particular institutional coordination of critical infrastructures and society.

3.3.3.3 Organizational risk theory and resilience engineering

Organizational sociologists have worked to understand how organizations respond to unpredictability and complexity of risks embedded in organizational management (Perrow, 1984; Rochlin et al., 1987; Roberts, 1990; Reason, 1997; Grote et al., 2009). Human factors and organizational characteristics were the main research domains for Perrow's normal accidents theory and High Reliability Organizational theorists. An important research question for both is about how organizations prepare for, respond to, and recover from disastrous events with high risks but low probabilities (i.e., longtail failures). Perrow's approach is more pessimistic and suggests forgiving these high-risk technologies. For instance, Perrow (1984), an organizational sociologist, contends that accidents are inevitable in case of type II organizations (e.g., nuclear power plant, nuclear weapons) (**Table 1**). In this category, tightly coupled organizations and sub-organizations cannot escape from accidents due to frequent feedbacks/ interconnectedness and unstoppable processes. For these organizations, accidents are normal. Perrow (1984) further maintains that the only way to avoid this type of risks is to abandon the related technologies. However, according to Perrow (1984), accidents from the other types of risks (I, III, IV) can be prevented with technological and institutional improvements (p.97).

Table 1. System failure risks

Interactions	Linear	Complex
Tight	Group I (Marine transport, Dams, Power grids,)	Group II (Nuclear Plant/ Weapons)
Coupling		
Loose	Group III (Traffic Accident)	Group IV (Mining, R&D firms)

(source: Perrow, 1984, p. 97; p.349)

Perrow's (1984) normal accident theory highlights human errors and structural organization failures rather than technical mishaps in analyzing unpredictable accidents.

However, High Risk Organization theory (Roberts, 1990; Rochlin et al., 1987) and Reason's (1997) Swiss Cheese model also discuss organizational failures but propose a few sociotechnical design principles, in a positive way, such as redundancy, institutional feedback loops, managerial flexibility to prevent failures to overcome the embedded probability of system failures. Recently, in safety engineering field, with reflection on asymmetry in explaining engineering failures—Hollnagel (2011) developed a perspective that failures should be explained by the same framework with organizational successes— Hollnagel et al. (2011) emphasizes salient processes (sensing, learning, responding, and anticipating) which render sociotechnical management successful.

Despite insightful implications of these sociotechnical systems perspectives above, Hollangel et al.'s (2011) framework, however, has no specific explanation on how to combine technical rigorousness and societal flexibility. For instance, Hollnagel et al.'s (2011) process approach (*sensing, learning, responding, and anticipating*) includes a limitation of obscurity about sensing, learning, responding, and anticipating 'of what'/ 'to what'? Each sociotechnical process needs each objective to sense, learn from, respond to, and anticipate. The knowledge processes inevitably assess ontological conditions and include the result of technological assessments for the epistemic management of infrastructures. In other words, each of Hollnagel's processes has deep liaison with the outcome of a previous process (e.g., anticipating 'something' based on the outcome of sensing). Sociotechnical theorists' proposal of institutional governance provides an insight on how to make harmonious coordination between different sub-organizational work groups (e.g., engineers, managers, and operators), which have different epistemic cultures and imaginaries for work procedures and structures (Jasanoff & Wynne, 1998, p.17). Sociotechnical theorists mention 'humans,' but humans and social groups are heterogeneous.

3.3.3.4 Social-ecological resilience

Scholars interested in the governance of natural resources proposed a social-ecological perspective to connect social and ecological system (Berkes & Folke, 1998; Folke, 2006). They defined the resilience of a socio-ecological system as "a capacity of a system to absorb disturbance and reorganize while undergoing changes so as to still retain essentially the same function, structure, and feedbacks, and identity" (Folke et al., 2010, p. 3). According to Holling (1973), if a system is continuously evolving and changing, rather than static, the pictures of renewal and re-organization of complex adaptive systems are more accurate than a simple description of recovery (Folke, 2006). In complex adaptive systems such as ecosystems, “uncertainty and surprise are part of the game” (Folke, 2006, p.255). Their focus was on resilient governance to retain the persistent performance of social-ecological system while adapting to new environments. They pay attention to responsive interactions of social systems to natural resources from ecological systems. The operation, management, and planning of infrastructures for natural resources are usually based on particular norms and rules called institutions, that is, social and human-made soft infrastructures (Anderies et al., 2004; 2013; 2015).

Social-ecologists perceive institutions as a vital component to retain the resilience of social-ecological system. Given the dynamics of natural and social environments, resilient systems should be both adaptive and persistent (Folke, 2006, p.259). Folke and his colleagues (2010) look into institutional adaptation and flexibility to contribute to the resilience quality of an ecological system. In their research, the traditional knowledge of local communities on ecological systems turned out to be sustainable community-based management of environmental resources. Scholars who work on social-ecological interactions also observe social-ecological institutions as *social capital* built in the governance of ecological systems (Folke et al., 1996; Folke and Berkes, 1995; Ostrom, 1990; Ostrom & Ahn, 2000).

Specifically, Holling’s (1973) complex adaptive system provided a foundation for the emergence of social-ecological system resilience (Folke, 2006, p.257), which focuses on *governance*. All of the renewal activities for new opportunities are essentially related to *governance arrangements*. Berkes & Folke's (1998) social-ecological perspective investigates *governance* over interactions between natural resources and society. Moreover, the establishment of adaptive governance, in accordance with 'risk society' (Beck, 1986) 'technological humility' (Jasanoff, 1993) 'risk at a turning point' (Stirling, 1999) 'risk governance' (Asselt & Renn, 2011) can be possible only through "the collaboration of a diverse set of stakeholders operating at different social and ecological scales in multi-level institutions and organizations" (Folke, 2006, p.262).

The social-ecological resilience insight on *governance* also resonates with Stirling (1999). As Stirling (1999) stated, risk assessment should be a vector with divergent dimensions, the proposing of a numerical answer to 'puzzles' in society, and "fuzzy and controversial socio-political problems." The goal of risk assessment should be "mapping the sensitivities of results to divergent assumptions" rather than the "single determinate quantity" (Stirling, 1999, p.123). All the incommensurable preferences in society cannot be merged through a simple risk assessment based on a narrow perspective, singular and solely rational process. Thus, if probability cannot be calculated and outcome cannot be measured, a policy should be made on the basis of the "ignorance" framework. The various dimensions of risk, such as severity, immediacy, duration, reversibility, familiarity, controllability, cannot be put into "a single objective ordering of social priorities" (Stirling, 1999). Every society (community) has its own perspective on the world, which is incarnated in incommensurable values, cultures, institutions, and modes of creation (Stirling, 1999; Jasanoff, 1993). A singular solution (formula) for social problems cannot be useful and, rather, be an illusion given the dynamics of the world.

Social and institutional *governance* is necessary for both *risk* and *resilience*.

3.4 Sociotechnical Resilience Variations: *Product vs. Process*

The definitions and standards of resilience are plural depending on different sectors and disciplines, and essentially linked to a question: is resilience a *product* or a *process*? (Pimm, 1986; Holling, 1996; Hollnagel, 2011b; Southwick et al., 2014; Mathias et al., 2018). Evolutionary resilience conception is more interested in the process of building resilience than a singular quantified equilibrium (Davoudi et al. 2013; Boschma, 2014). Engineering scholarship has traditionally emphasized *product* resilience: the capacity of a specific physical system or technical components to rebound after exposure to extreme events (Pimm, 1991). Thus, product assessments which measure robustness and rapidity are seen as key guidelines of resilience: the ability to withstand external shock robustly and the ability to bounce back rapidly to a previous status quo (e.g., Chang & Shinozuka 2004; McDaniels et al. 2008; Bruneau et al. 2005, p. 19; Ouyang, 2017). In engineering, this is often framed as optimizing whether physical infrastructure can robustly retain or restore its functionality to an original equilibrium point when exposed to a variety of stressors (Pimm, 1991; Wang & Blackmore, 2009).

On the other hand, the relatively new fields of safety engineering and resilience engineering emphasize organizational response and *processes* within a complex, often unpredictable sociotechnical system (Hollnagel & Nemeth, 2009). Hollnagel defines resilience as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain the required operations under both expected and unexpected conditions” (2011a, p.xxxvi). Hollnagel (2011b) further emphasizes four human *processes*—sensing (monitoring), learning, responding, and anticipating—for infrastructure resilience, and casts doubt on the proposition of a static equilibrium outcome. Park et al. (2013) interprets *safe-to-fail* strategies as a process rather than a product while referring to resilience as a quality instead of a quantity. “From a non-equilibrium perspective,” fail-safe risk assessment based on static provisions for disturbances is paradoxically non-sustainable given nonlinear circumstances (Ahern, 2011, p.341). The notion emphasizing *safe-to-fail* resilience is a result of contemplation on this paradox that critical infrastructure needs to be both resilient against disruption in the short term while capable of adaptation and transformation over the long term (Ahern, 2011). As seen in the definition of resilience by UN/ISDR (2004), for instance, the *process* aspect of resilience is crucial:

> Resilience is **a capacity** of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for **learning from past disasters** for better future protection and to improve risk reduction measures. (UN/ISDR 2004, p.16, emphasis added by authors)

However, infrastructure resilience should be understood from the perspective of institutions. Institutions are deeply involved in this dynamic interplay between resilience as a stable product and as a flexible process. Mathias et al. (2018) maintains the dynamic aspects of resilience but fails to fully articulate the justification of this notion. Despite Mathias et al.'s (2018) work, this research argues that detailed efforts to understand the relationship between infrastructure resilience and complex institutional mediation are still required to better elaborate the coordination between process and product. Neither engineering statistics nor a qualitative process (e.g., resilience engineering) matches both infrastructural and institutional dynamics. This research holds that the summation of *differential* (short-term) assessments and institutional stability compose the long-term *integral* curves and institutional flexibility.

3.5 Wildavsky's (1988) Notion: Over the dichotomy

However, the question, here, remains as to what kind of governance is need. For instance, in public administration associated with governing risks, there has been a long tradition of debates between outcome and process. In general, how the efficacy of public policy could be measured or how to evaluate the accomplishments of a governmental official has been a critical question to the implementation of public policies. In particular, with respect to risk governance, Wildavsky's (1988) comparison between resilience, which "accommodates variability" and anticipation, which "seeks to preserve stability" (Wildavsky, 1988, p.78), epitomizes the debate between *process vs. outcome*. According to Wildavsky (1988), "under considerable uncertainty, resilience is the preferable strategy. Under substantial certainty, anticipation does make sense." In detail, Wildavsky (1988) maintains that if resilience is more suitable for risks which derive from "unpredictable or low probability source." Wildavsky's (1988) great insight is imbued and harmonized with *resilience engineering*.

The *uncertainty* of risks as well as the emphasis on *governance* by resilience stresses an innovative perspective, called resilience engineering. This perspective focuses on *process* rather than *product* (outcome). For instance, *engineering resilience* and *Safe-to-fail* strategies as a process for uncertain risks are preferred rather than a product and quantified resilience. Fail-safe risk assessment based on static provisions for disturbances is paradoxically non-sustainable given nonlinear circumstances (Park et al., 2013). However, safe-to-fail, process-based resilience can easily lack rigorous anticipation. As Wildavsky (1988) stated, "[A]ll resilience, no anticipation, or vice versa—would be destructive." Recognition of this dilemma asks infrastructure to be both stable and resilient against disruptions. Resilience engineering missed Wildavsky's (1988) caveat on the difficulty in developing the optimal mixture of anticipation and resilience (p.85).

This research maintains that process-based approaches well reflect the implications from the development of modern risks and resilience: uncertainty, ambiguity, complex society, and governance structure. According to Scott (1998), modern science perspectives—e.g., statistics, economics, etc.—which contribute to the foundation of modern states, contain errors in logic. Modern assessment methodologies inherently ignore the diversity of nature and society and reduce them into abstract numbers and formula (Porter, 1995). The process of mapping resources such as lands, people, and nature cannot avoid simplifying diversity. To avoid this fallacy, resilience engineering and other developments of risk discussions have improved governance and incremental process approaches. Thus, given the nonlinearity of climate change, adaptive anticipations of risk governance, and resilience engineering for infrastructure flexibility fit in tasks of infrastructure resilience in response to climate challenges. Yet how to make an optimum of combination between anticipation and resilience is a fundamental inquiry to infrastructure resilience. As Wildavsky (1988) stated, a central problem with risk governance should be how to keep balancing between the rigorousness of methodologies and the harmonious processes that add social values and desires to paint rigorousness.

3.6 From *Risk vs. Resilience* to *Sociotechnical Resilience*

In order to answer the query on balancing (Wildavsky, 1988), in my opinion, the meaning of *risk* should be revisted and critically examined here.

In general, the assessments and management of risks has been largely regarded as preparatory treatments to prevent harmful events from occurring or to constrain dangerous human activities in order to protect society. Conversely, (engineering) resilience is a new notion that focuses on recovery which basically aims at bouncing back and even further re-organization in the recognition of characteristics of modern risks: *uncertainties* and *unavoidability*.

However, in this research, risk is viewed as inherently uncertain and unavoidable (see Renn, 2008; Renn, Klinke, and Asselt, 2011; Asselt and Renn, 2011 on '*risk governance*'). Resilience engineering scholars (Hollnagel, 2011; Park et al., 2013) demarcate identified hazards for risk assessments from unidentified causes for resilience. However, given the contextual complexity and expanded scales (e.g., temporal and geospatial) of realities wherein identified hazards (risk assessments) (Jasanoff, 1993) are always situated, there is an argument to be made for reconsidering the demarcation between risk and resilience.

In particular, Jasanoff's (1993) effort to bridge qualitative and quantitative risk conceptions already takes into consideration the limitation of dichotomy that Wildavsky (1988) pointed out with his notion of the mixture between anticipation and resilience. There is no risk which is not complex and has a clear boundary. Life is intrinsically uncertain. No risk can be isolated from society given the social co-production of risk knowledge. Ontological things and epistemological conceptions are always convoluted and rarely static in an era of uncertainties and complexity. In an era defined by the uncertainties of risks, then, scales not demarcation are crucial questions to defining resilience.

Therefore, in terms of infrastructure resilience, this research asserts that resilience emphasis should move on to discussions on the human and social dimensions of resilience, and temporal and geospatial scales, not the demarcation framework (e.g., Park et al., 2013) between quantitative and qualitative risks: *sociotechnical resilience*. How to sustain infrastructure in the short-term, adapt in the mid-term, and transform in the long-term with detailed institutional governance should be a more critical question to infrastructure resilience than the linear demarcation between risk assessment and resilience. For instance, engineering bouncing back in the short-term, multiple adaptations in the mid-term, and innovative transformation in the long-term can be a potential strategy for infrastructure in response to nonlinearity and uncertainties of climate change.

3.7 Overcoming the Weakness of Sociotechnical Systems Theory: Focusing on Institutional Dynamics

However, with the goal of explaining infrastructure resilience in mind, to explain infrastructure resilience, however, more in-depth understanding of institutional dynamics incorporating quantified risks and qualitative resilience is needed. Infrastructure should sustain its equilibrium while being adaptive and even transformative in response to changing conditions (e.g., social and environmental changes). To be sustainable, as Bertalanffy (1933) and other system theorists stated, a system should be open to environments and sustain its homeostasis in the short term via sound feedback loops. Infrastructure should also be static as well as flexible to adapt to environments. Many scholars in the sociotechnical systems area overlooked the sustaining role of institutions and the importance of the persistent management of infrastructure. Not only adaptation but also sustaining is an essential component of resilience management. Sociotechnical systems theory is limited to explaining how the dynamic iteration of infrastructural stability and adaptations emerge and converge, which is critical to resilience.

In particular, social institutions can settle a specific goal for the management of infrastructure per a fixed goal and a linear pathway in the short term. At a particular given moment, a derivative (a gradient) on an infrastructural curve can be well-defined, and organizational institutions easily quantify embedded conditions and determine the trajectory—"the pattern of normal problem solving activity….on the ground of a technological paradigm (Dosi, 1982, p.152; Kunneke & Groenewegen, 2009, p.8)"—of infrastructure while aiming at a specific outcome. In case of uncertainties, institutions which govern infrastructure can aim for a *process* rather than a *product*. Chasing a non-stationary target with a fixed trajectory is a useless effort because 'we do not know where it goes.' Different directions (or organizational goals) should be coordinated for a long-term goal. In order to help to understand the dynamics of sociotechnical systems, **Fig. 3** has been created and refined throughout this research and will be explained in the following paragraphs.

More specifically, institutions should support infrastructural stability and have a tendency for a stable equilibrium in the short term as seen on the point of Ⓐ (**Fig. 3**). Organizational goals and institutional settings should be clear and stable in the short term as are at the point of Ⓐ. In the mid-term, institutions should interplay between stability and flexibility. A gradient (a derivative) on Ⓐ, which is calculated by differentiation, illustrates a direction of incremental increase of a variable (e.g., traffic flow) associated with infrastructural management. However, it is also evident that the gradient, which implies the infrastructural pathway during the time period of t0 – t1 (from Ⓐ to Ⓑ), shows a positive slope. However, the gradient during t0 – t2 (from Ⓐ to Ⓒ) shows a negative slope. It is true that the infrastructural curve declines during the duration of t0—t1 but goes up during the duration of t1—t2. This means infrastructural management and its goals should be adaptive in accordance with temporal changes in the mid-term.

Moreover, institutions should work for transformational changes in infrastructure systems in the long term. During the longer time duration of t0 – t3, uncertainties associated with infrastructural management can make it almost impossible for an organization to set an explicit quantitative goal for infrastructure. For instance, it is not a simple question to an organization of transportation management which point should be targeted between Ⓓ or Ⓔ as an organizational goal associated with traffic flows and transportation system planning in the long term. Organizational management and strategies for the pathway from Ⓐ to Ⓓ must be different from goals and strategies of the organizational pathway from Ⓐ to Ⓔ. More specifically, in case of the duration t0—t3, it is uncertain that infrastructure will pass through Ⓓ or Ⓔ. Under these uncertain circumstances, it is more strategic with respect to institutional management to make agreed-upon flexible *processes* by which an organization keeps moving forward towards an interim goal rather than to track a fixed trajectory and target a stationary goal. As such, institutions should work for the consolidation of infrastructure in the short term. However, institutions should be adaptive in the mid-term and transformative in the long term. It is questionable that sociotechnical systems theory has a detailed explanation on institutional dynamics as stated above.

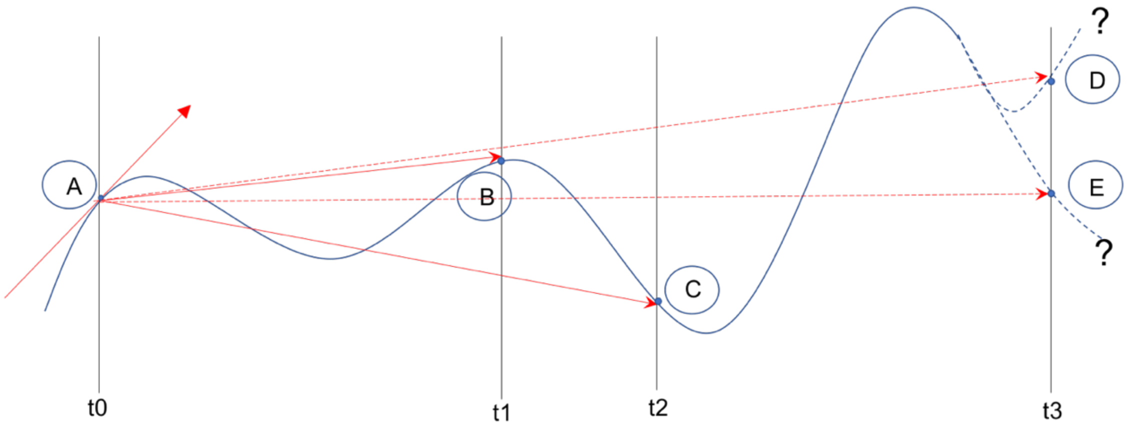

Figure 3. Infrastructural stability and dynamics (source: Changdeok Gim, author)

3.8 Other Limitations of Sociotechnical Systems Theory in Explaining Resilience

First, sociotechnical systems theory has not been developed to explain coupled systems (Mumford, 2006). Infrastructure and organizations are "moving away from hierarchies to networks (Castells, 1996) and from centralized to decentralized structures in which parts of a company are run as semi-autonomous units" (Mumford, 2006, p. 335). In the UK, the Tavistock Institute in the 1960s developed the sociotechnical approach more deeply and applied this to many work fields such as coal mining. However, the initial application and theoretical background have no consideration of coupled systems. Interdependent networks, robust yet fragile systems (Alderson & Doyle, 2010), put much emphasis on the coordination between systems (Rinaldi et al., 2001). However, since Thompson (1964) categorized three types of organizational interdependence (e.g., pooled, sequential, and reciprocal), research studies on sociotechnical systems theory raely have an explanation on how the two different systems are institutionally and organizationally interdependent and coordinate with each counterpart for infrastructure resilience. As Hughes (1983) and Mumford (2006) pointed out, the deep understanding of interdependence issues is a prerequisite to analyzing infrastructure resilience.

Second, sociotechnical systems theory cannot explain the process and contexts for the co-production of sociotechnical resilience. As Miller & Muñoz-Erickson (2018) stated, "knowledge doesn't just appear in magic. (…) In turn, knowledge systems filter, manipulated, and represent the data and information that come out the other end" (p.3). Institutions, as embedded knowledge (Collins, 1993), are produced, validated, circulated, and consumed by social organizations. What is important with this process is institutions are also 'filtered, chosen, and manipulated' by particular organizations. Latour's (1991) notion on scientific knowledge is also congruent with Miller & Muñoz-Erickson's (2018) knowledge systems argument.

> The facts are produced and represented in the laboratory, in scientific writings: they are recognized and vouched for by the nascent community of witnesses. Scientists are scrupulous representatives of the facts (Latour, 1991, p.28).

Sociotechnical systems theory postulates the neutrality of data, information, and knowledge, but institutions are essentially co-produced outcomes by the very particular arrangements between society and technoscience (knowledge systems) (**Fig. 4**).

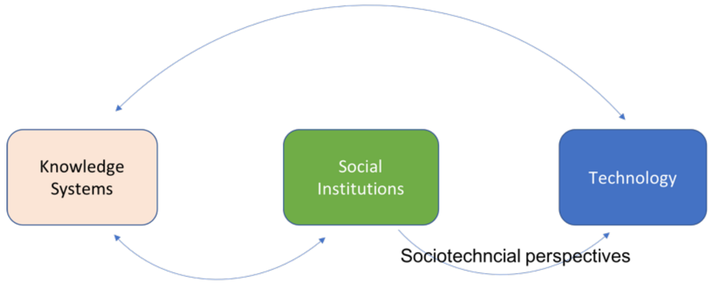

Figure 4. The comparison between the knowledge systems and sociotechnical perspective (source: Changdeok Gim, author)

This shortcoming hampers the possibility of having a broader overview on the social production of infrastructure resilience. How infrastructural resilience can be socially constructed is also a critical question for society and should be reflected on in the process of the knowledge co-production (Miller, 2017; Miller & Muñoz-Erickson, 2018; Miller & Wyborn, 2018) of 'resilience.' Who participates, in what ways, and to what effect infrastructure resilience should be co-produced is a grave question for society.

> [D]esign is never just technical but always sociotechnical, raising important questions about who participates, in what ways, and to what effect. Equally important are questions of how design choices ultimately intersect with the arrangements and dynamics of social networks and relationships (Miller, 2017, p.910).

In line with the second weakness of sociotechnical systems theory, the third weak point of sociotechnical systems theory is based on Latour's (1991) critique on social constructivism. According to Latour (1991, p.94), the social construction of science and technology is asymmetrical. Both nature and society should be symmetrically explained by identical principles (generalized symmetry) and thus infrastructure, quasi-objects, are already an assemblage of 'sociomaterial practices' (Orlinkowski, 2007). In other words, sociotechnical systems' perspective on the social influence on technical components is an asymmetric diagnosis according to Latour (1991). As Hughes earlier wrote,

> Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping… (Hughes, 1983, p. 51).

The world is full of quasi-objects and myriad of networks composed of 'actants,' and thus social institutions and technological apparatuses have been mutually shaped by each other to date. In this sense, the influence of technologies is also important to shaping society and should be evaluated as a symmetric contribution to the constitution of networks from the counterpart. Infrastructure, from Latour's perspective, is an assemblage of social and technological networks and should not be regarded as different from a user or a utility, which is interpreted as an actant by Actor Network Theory (ANT). According to Latour (1991), when it comes to the resilience of infrastructure, how society can be impacted by technologies and be shaped towards resilience through the co-production of networks of quasi-objects should be an important question for society to consider. If sociotechnical systems theory only aims at the explanation of social influences on technologies, the resulting perspective is too myopic and can miss the macro-level overview of the relationship between society and technoscience (Edward, 2003).

> But taken alone, without attention to meso- and macro-scale analysis, constructivism creates a myopic view of relations among technology, society, and nature (Edwards, 2003, p.28).

> Thus, it is asymmetrical not because it separates ideology and science, as epistemologists do, but because it brackets off Nature and makes the 'Society' pole carry the full weight of explanation (Latour, 1991, p.94).

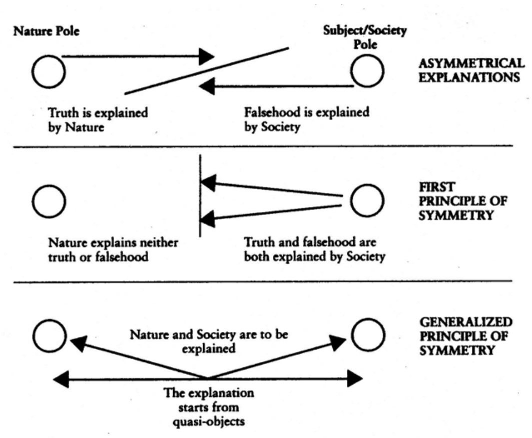

Figure 5. The principle of symmetry

(source: Latour, 1991, p.94)

Lastly, sociotechnical frameworks fail to integrate users and institutions into sociotechnical systems to elucidate the resilience of infrastructures. The sociotechnical systems perspectives emerged to explain the managerial risks of systems and transitioned a narrow, technical perspective on systems into a more comprehensive frame, but fails to thoroughly investigate the dynamics of institutions, users, and organizations in response to the emergence of uncertainties. Furthermore, if we include ecological dimensions of infrastructures, the sociotechnical systems perspective is not suitable for examining the relationship between society, technologies, and ecological environments. A more holistic framework (e.g., socio-tech-ecological framework) needs to be developed for analyses on the resilience concept embedded in socio-tech-environmental systems (Markolf et al., 2019)

3.9 Conclusion

Resilience originates from the rejection of quantified risks, but risks are by definition both quantitative and qualitative given the complexity and uncertainties of risks (Jasanoff, 1993). The sociotechnical systems perspective does not fully explain how to incorporate both robust quantification and flexible qualitative approaches with respect to infrastructural dynamics. Wildavsky (1988) proposes an alternative mixture of anticipation and resilience for risk management. In other words, to manage physical and social challenges, namely risks to infrastructures, the management of infrastructure should deal with the boundary dilemma between stability and flexibility (or adaptiveness). Dietz et al. (2003) revealed that coupled institutions facilitating the exchange of information and enhancing the centralized decision-making system for the rapidity of system performance can, on the contrary, hamper the recovery and resilience of a system. A locally adaptive goal can also prompt a global maladaptation (Woods, 2011). Besides, tangled layered network system can easily lead to the increase of embedded cost related to risk management (Weick et al., 2005).

A solution to this dilemma can be found in institutional management. On this point, the sociotechnical consideration of infrastructure resilience has a critical implication. Institutions can be stable in the short-term, but also can be adaptive in the long-term. In other words, sociotechnical infrastructure systems cannot be resilient without being properly operated, managed, and planned by people and institutions either on a small or large scale. In a socio-technological system, maintaining a resilient infrastructure frequently means a proper operation, management, and planning of infrastructures by quantified assessments, mediated regulations, and qualitative social agreements or political processes within which institutions play out. Thus, enhancing the resilience of infrastructures necessarily incorporates investigating particular institutional settings and organizational behaviors. The next chapter, in detail, will investigate this resilience work by institutions and institutional interdependencies of sociotechnical infrastructures.

CHAPTER 4

INSTITUTIONAL THREADS, RESILIENCE WORK, AND INSTITUTIONAL INTERDEPENDENCES IN SOCIOTECHNICAL SYSTEMS

4.1 Introduction

Chapter 4 shows how institutions sustain, adapt, and transform the structure and process of a system to withstand and absorb internal and external disturbances which is conceived of as resilience capacity. To this end, Chapter 4 illustrates how the complex work of different institutions are layered over infrastructures through vertical, lateral, and longitudinal threads. These overlapping and interacting institutions play a critical role in sustaining, adapting, and transforming sociotechnical systems in the face of the resilience challenge of balancing stability and flexibility. In other words, how the resilience work of institutions sustains stability, adapts rules, and transforms the governance of infrastructures with divergent goals, strategies, organizational levels, and distinct resilience frameworks at different temporal scales should be a question for infrastructure resilience. This work occurs across multiple levels of functionality, including operational, regulatory, and constitutional work, through which institutions seek to achieve infrastructure resilience via minute, adaptive, and transformational change, which, respectively, optimize, reconfigure, and redesign infrastructure. Social institutions also manage infrastructure for resilience at different temporal scales: in the short-term infrastructure is sustained to resist disruption; in the mid-term it must make infrastructure adaptable; and in the long-term it must be capable of fundamentally transforming the sociotechnical infrastructure when necessary. Together, these multiple dimensions of overlapping and intersecting institutional work create interdependence.

4.2 Institutional Approach to Sociotechnical Infrastructures

An institutional approach to sociotechnical systems is not new. Kunneke, R. W., Knops, H. P. A. and Vries, L. J. de. (2007) proposed an institutional analysis framework that emphasizes co-evolution and coordination between institutions and infrastructure. In addtion, Kunneke & Gronewegen (2009) introduced an institutional layering model for the analysis of sociotechnical infrastructure. They defined infrastructure as "complex sociotechnical systems in which institutions and technology are strongly interwoven." (Kunneke & Gronewegen, 2009, p. 5). They divided institutional governance for infrastructure into three types: institutional arrangements, formal, and informal institutions. First, "informal and embedded institutions" have a long-term period of updating (e.g., 100 or 1000 years) and are characterized by their independence from governmental intervention. Secondly, the formal institutional layer includes formal legal institutions such as 'constitutions, laws and regulations'. Typically, these formal institutions are updated within a time scale of decades. They rule political power dynamics, economic activities (e.g., property rights) judiciary ordering, and governmental administration. Lastly, institutional arrangements include private contracts, and organizational, cooperative protocols which are revised within one year and a decade. Then, Kunneke (2010) applied this framework to understand bottom-up, user-driven, and self-organizing infrastructure, such as Wi-Fi networks. Their analysis sheds light on the conception of coherent development of society and technology and helps to understand the sociotechnical dimensions of infrastructure.

4.2.1. A critique of Kunneke and Gronewegen (2009)

However, from my viewpoint, Kunneke & Gronewegen's (2009) framework reveals a misunderstanding of institutional categorization. In particular, as formal institutions, each individual formal institution (e.g., constitutions, laws, regulations) has distinctive amendment cycles and functional roles in governing infrastructure. Infrastructural governance can be better understood with the full appreciation of the dynamics of institutional stability and adaptability at different temporal scales and layered levels. ii) Their institutional framework interprets contracts (institutional arrangements) as institutions, but contracts are different from generalized rules, institutions which have a broader application scope for other organizational members beyond contractors. iii) Furthermore, the separation and boundaries between formal and informal institutions is not binary and never static. For instance, informal social custom can be transitioned into customary law—legally binding institutions—with the acquisition of a social confirmation of law (*opinion juris*) (Dahlman, 2012). More importantly, yet, the sociotechnical frameworks, including Kunneke & Gronewegen (2009), do not fully understand the dynamics and inherent dilemmas that infrastructures face, which are critical to infrastructural management for resilience. The detailed dynamics of institutions can first be understood by analyzing the structure of institutional threads of sociotechnical systems.

The following sections will explain institutional threads, a new conception of the inherent boundary dilemma to infrastructure resilience, and institutional interdependencies.

4.2.2 Institutional threads and types of institutions

Table 2. Institutional threads and three types of institutions (source: author)

Institutional threads and functions	**Definitions**
Vertical thread	The hierarchical, institutional governance in a single organization or multiple organizations
Lateral thread	The horizontal structure of institutional governance in different levels of organizations
Longitudinal thread	The temporal dimension of institutional governance over organizational structure (e.g., temporal patterns of short-term, mid-term, and long-term management and historical accumulation of institutional development
Institutional functions	The respective functions of institutions for managing infrastructures (e.g., operational maintenance for daily and monthly routines, regulatory adaptation for correction, and reconstitution for transformation)

The structure of infrastructure has three types of threads of institutions: vertical, lateral, and longitudinal threads. To analyze institutional structure, first, it is necessary to untangle institutional threads tangled in interdependence networks. Social systems (e.g., families, social groups, companies, local governments, and nation-states) and institutions for organizations of people have multi-dimensional threads of governance. Three forms of institutional threads support the structure of infrastructures: the *vertical threads* govern organizations at different hierarchical levels; the *lateral threads* exist among organizations and institutions in different domains or systems at the same level; and the *longitudinal threads* of cultural/political heritage and temporal management over time. The functions of operational, regulatory, and constitutional institutions manage the functionality of infrastructures nested in three-dimensional arrangements; vertical, lateral, and longitudinal threads.

The functions of institutions can be categorized into three types: operational, regulatory, and constitutional institutions. **Operational institutions** manage and operate physical infrastructures while sustaining a static matter, infrastructural stability with a specified goal. **Regulatory institutions** are a more adaptive governance tool, which is involved in updating institutions and reconfiguring physical infrastructures instead of supporting a static equilibrium. **Constitutional institutions** induce infrastructural transformation—which means a systemic change into a different state because preceding infrastructural settings cannot hold the same character and need significant alterations in institutional arrangements and physical configurations—in the long-term. The following sections unbundle these institutional threads.

4.3 Unbundling Institutional Threads: Vertical, Lateral, and Longitudinal Threads

This section unbundles different types of institutional threads (i.e., vertical, lateral, and longitudinal layers), which wrap infrastructures and arrange institutional settings for resilience work of institutions. These threads also become conduits for trade-offs in infrastructural networks.

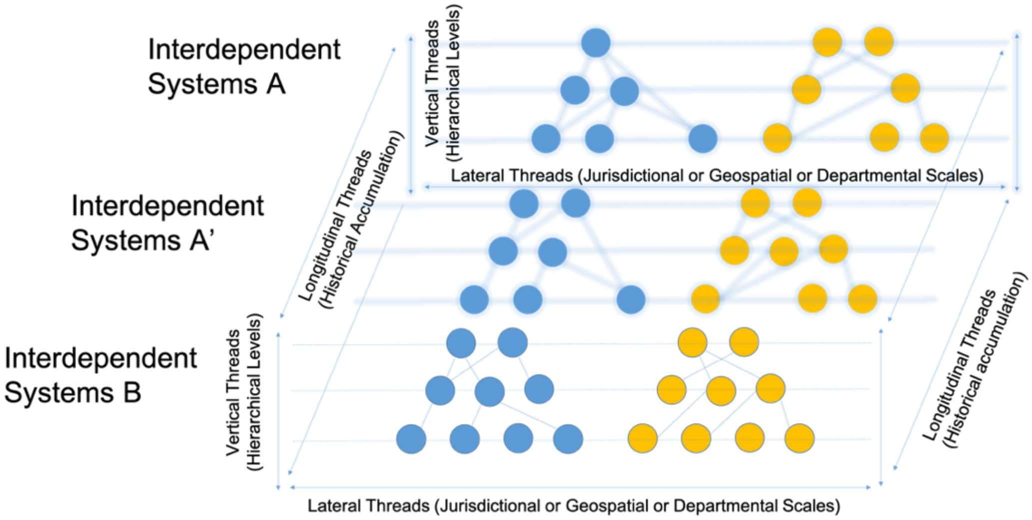

Figure 6. The structure of institutional threads wrapping infrastructures (source: Changdeok Gim, author)

4.3.1 The vertical thread: hierarchy—organizations at different *hierarchical levels*—directs and defines the relationship between higher/macro, middle/meso, and lower/micro level agents, organizations, and infrastructures. Hierarchical institutions, *hierarchy*, make an order in social organizations. A system "is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure (…)" (Simon, 1962, pp. 468-9). "Business firms, governments, universities all have a clearly visible parts-within-parts structure," as do biological systems (p. 469). The institutional hierarchy in institutional orders span jurisdictional authorities (e.g., municipality/state/federal government), corporation ownership structure (e.g., proprietary and subsidiary companies), and regulatory oversight hierarchy (e.g., Nuclear Regulatory Commission and nuclear power plants).

The first fundamental difference between engineering systems and sociotechnical systems depicted in **Fig. 6** is the consideration of institutional structures. The political governance in the United States has examples of hierarchical interventions from the ideology of ‘Federalists’ despite a mixture of vertical directions and devolution of political power. The adjudication of the state courts is subordinate to the judgment of the U.S. federal courts (the U.S. District Court and U.S. Courts of Appeals) in federal law related disputes. Also, the EPA provides a standard for air quality regulations (e.g., the National Ambient Air Quality Standard, NAAQS) and requires states to submit a State Implementation Plan (SIP) to the EPA for approval (Konisky & Woods, 2016, p.376).

> “Under the Clean Air Act, for instance, each state must have an EPA-approved State Implementation Plan that governs how it is to attempt to achieve federal regulatory goals. If the EPA finds that some portion of a state’s SIP is inadequate, it can impose its own Federal Implementation Plan covering that portion.” (Konisky & Woods, 2016, p. 376)

42 U.S.C.

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Title 42 - THE PUBLIC HEALTH AND WELFARE

CHAPTER 85 - AIR POLLUTION PREVENTION AND CONTROL

SUBCHAPTER I - PROGRAMS AND ACTIVITIES

Part A - Air Quality and Emission Limitations

Sec. 7407 - Air quality control regions

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§7407. Air quality control regions

(a) Responsibility of each State for air quality; submission of implementation plan

Each State shall have the primary responsibility for assuring air quality within the entire geographic area comprising such State by submitting an implementation plan for such State which will specify the manner in which **national primary and secondary ambient air quality standards will be achieved and maintained within each air quality control region in such State**.

The vertical thread is a unique political feature and the reification of ideologies from both Federalists and Anti-Federalists in the US.

> These early “federalists” thus advocated little more than an expansion of congressional authority under the loose union of the Articles of Confederation. (…) More analytical essays pointed to defects in specific provisions, concentrating heavily on the small size and broad powers of the federal legislature. Anti-federalists also revived a dispute that figured heavily in the Federal Convention itself: that the Convention had exceeded its authority (Farber & Sherry, 1990, p.175; p. 178).

(about the debate on Federalists versus Anti-Federalists, see Farber & Sherry, 1990, *A history of the American Constitution, pp.175-180*).

4.3.2 The lateral thread: Infrastructures have lateral threads to connect different domains or systems at distinctive organizational or geospatial scales. Lateral governance occurs as a result of the traditional siloing of organizations according to geographical, administrative, disciplinary, professional, system, or other boundaries. Within domains or systems, organizations develop specific forms of knowledge and social practices (Miller and Muñoz-Erickson, 2018) that tend to diverge from those operating in similar organizations in other nearby or even interdependent domains, across distinct, e.g., government departments, utilities, advocacy groups, or markets. These organizations may cooperate and exchange information, data, services, and resources, in order to facilitate coordination within or across individual infrastructure systems. Or, they may compete with one another for resources or power. Typically, the output from one organization becomes the input for the other organization and *vice versa*. Thompson (1967) called this 'reciprocal interdependence.' In this type of interdependence, one counterpart can 'pose contingency for the other' (Thompson, 1967, p.55). Nonetheless, these coordination and competition mechanisms are rarely perfect and often tend to disguise or hide differences from one institution to another in ways that can exacerbate vulnerabilities and reduce resilience. In this case, one organization's institutional changes in one system can affect the operation and management of system governance for the other organizations.

4.3.3 The longitudinal thread: Updating institutional arrangements for infrastructure resilience requires an understanding of the longitudinal heritage of institutions over time. The longitudinal accumulation of electoral voting, cultural beliefs, political contestation, and labor sabotage creates historical continuities as well as path dependencies in infrastructural contexts where decision making gets finalized and physically implemented in the form of real structures. Occasionally, infrastructural obduracy (Hommels, 2008) or path dependence (Bolton & Foxon, 2011; Unruh, 2000) hampers the adaptiveness of infrastructures to social changes and worsens vulnerabilities. Longitudinal threads are buried in invisible contexts rather than visible contents and become hard to detect. Thus, the amendment of historical and cultural paths requires sophisticated approaches. For instance, the monolithic historical remnants that Confucian cultures embedded in communication protocols blocked feedback between chief and assistant pilots and resulted in a fatal crash (223 deaths) of a Korean Airline passenger airplane in 1997 (Malcom Gladwell, 2008, *Outlier*s) in Guam. Moreover, longitudinal dimensions have more narrowed institutional arrangements that operate on different temporal dynamics. For example, in a related paper, I describe the short-term processes (minutes to months) through which management organizations operate infrastructures; medium-term processes (months to years) through which they adapt and upgrade them; and long-term processes (years to decades) through which they transform them via new construction (Gim, Miller & Hirt, 2019).

4.4. The Function of Institutions and Resilience Work

4.4.1 A problem statement on infrastructure resilience and knowledge transition:

boundary management

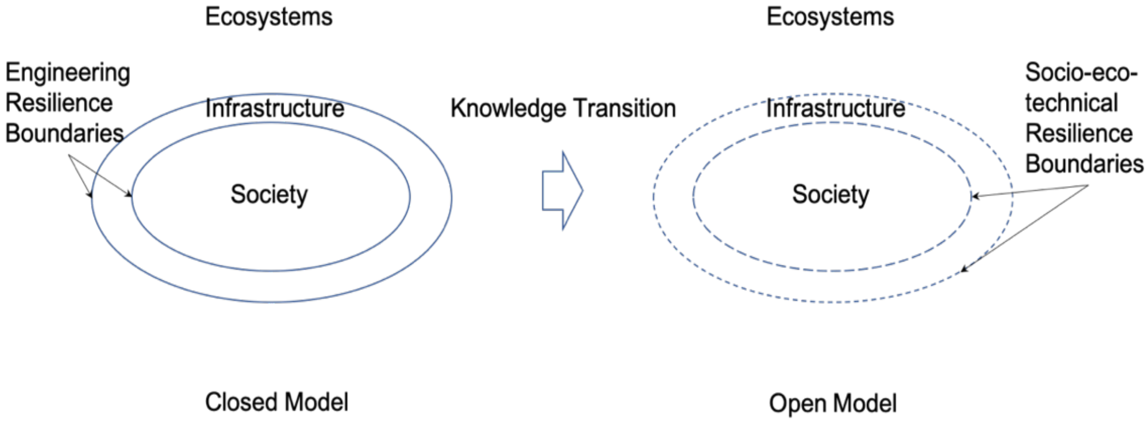

Figure 7. From a closed infrastructure model to a porous infrastructure model (knowledge adaptation and transition) (source: Changdeok Gim, author)

With respect to resilience, infrastructure has a boundary management problem. Infrastructures as open systems migrate across alternative phases when facing boundary dilemmas of institutions. Infrastructure is dynamic as well as open, and thus the institutional management of infrastructure should entail both stability and flexibility strategies. First, regarding environmental challenges, infrastructure should have the capability to sustain its functionality by dissociating its physical facilities from multiple natural interventions. Technical boundaries and physical visibility are quintessential qualities of urban infrastructures. Technological innovation in infrastructure engineering was mostly dedicated to rendering infrastructure boundaries discernible, defying nature's interventions. Technological innovations in the design and materiality of engineered technological apparatuses (e.g., dams, roads, rails, grids, aqueducts, and telecommunication towers), which indicate engineering resilience, all aim for lucid disconnection and consistent protection from ecological stressors and disruptions (e.g., frosting, erosion, flooding, destruction by water, air, fire, snow, hurricane, etc.). For instance, dikes confine surface water and protect the urban areas that urban residents inhabit.

4.4.2 Stable yet adaptive: *boundary challenges*

Multiple disciplines deal with the boundary management of open system dilemmas regarding stable yet adaptive boundaries. One of the conditions for the successful management of infrastructures as open systems has been focused on how to address boundary tensions between stability and flexibility with institutional capabilities. In the engineering field, a holistic system approach was proposed to maintain balance between engineering robustness and the adaptive flexibility of infrastructures to natural dynamics (Tempels & Hartmann, 2014). The social-ecological resilience field, in dealing with social dilemmas associated with the allocation of natural resources, tackle social-ecological boundary dilemmas on how to reconcile ecological fluctuations and sustainable yields with the management of soft infrastructures (i.e., institutional governance) in operating hard infrastructures (e.g., dams, dikes, canals, and fishery apparatuses) (Anderies, 2006; Janssen & Anderies, 2007). The accomplishment of both societal stability and ecological sustainability in confronting ecological variations via governance is a fundamental question to social-ecologists. As Wildavsky (1988) points out, in the political science area one of the challenges that the management of risks faces is the nuanced and balanced administration mixture between quantified anticipation for stability and resilience to uncertainties.

Science and Technology Studies (STS) also offers a unique stance on boundary tensions. As Star and Ruhleder (2005) stated, “an infrastructure occurs when the tension between local and global is resolved,” which means “an infrastructure occurs when local practices are afforded by a larger-scale technology, which can then be used in a natural, ready-to-hand fashion” (2005, p.6). Put differently, the “interpretive flexibility” of infrastructure can allow ‘design flexibility’ and “different appearances to different groups” while avoiding the simplification of infrastructure as materialities (Star and Ruhleder, 2005; Trompette & Vinck, 2010). Abiding by local boundaries while scaling up to global systems is only possible with knowledge reconfiguration and transitions across different temporal and geospatial scales. It is imperative to infrastructure resilience to analyze and investigate knowledge (institutional) transition, given the transitioning role of knowledge for boundary dilemmas of infrastructure—as a type of knowledge (Collins, 1993), which is an institutional task to understand risk and resilience.

4.5 Institutional Work and Resilience

Despite the recognition that institutions are critical to the effective functioning of infrastructure, most research and investment in the field of infrastructure resilience has prioritized the technological and physical upgrades of infrastructural systems over their institutional dimensions. For instance, the growing emphasis in engineering research and resilience policy on the interdependence of multiple infrastructure systems—such as water, energy, and transportation networks—tends to emphasize technological or physical interdependencies that create the possibility for failures to cascade across systems. A water shortage, for example, can impact the supply of water for cooling generators in thermoelectric power plants (Vliet et al. 2012). Electricity outages, in turn, can impede the delivery and treatment of water, halt the operation of rail and traffic signal systems, or prevent the supply of gasoline and natural gas required for myriad forms of transportation (Rinaldi et al. 2001; O'Rourke 2007).

The development and function of infrastructure depends not only on engineering outcomes of technologies but also on dynamic social processes. Infrastructure is more than just technology; it is made up of organizational structures and processes that link technology to social, economic, and political dynamics (Emery & Trist, 1960; Kunneke & Groenewegen, 2009; Bolton & Foxon, 2011). The supply of water for cooling thermoelectric generators is not just a chemical matrix of H_2O but a socially and technologically co-produced outcome: *engineered water in society*. At the macro scale, water for agricultural, urban, and industrial uses in Arizona has social value precisely because of the dams, canals, pipelines, treatment facilities, pumps and other infrastructure through which it is delivered, but also because of the institutional arrangements by which water infrastructure is built and maintained, water rights established and defended, and water quality standards adopted and enforced. Infrastructure, a 'robust-yet-fragile' system (Alderson and Doyle 2010) only successfully performs via complex institutional networks.

However, without engineering risk calibrations, the institutional arrangements cannot have standards. Without standards, institutional stability cannot be accomplished. For instance, water pump pressure should be optimized, and the quality of water needs to be standardized through engineering calculations. The stable trajectories of system resilience in the short-term comprise iterative engineering analyses for physical equilibrium, the optimization of components, and quantified recoveries (engineering resilience, Pimm, 1991). More importantly, these engineering calibrations are also dependent on knowledge matrices and institutional stabilities.

Therefore, the complementary work between engineering rigor for short-term stability and evolutionary processes for long-term adaptation arise through the resilience work of institutions (**Fig. 8**). Each outcome standard and social process, such as monitoring robustness, identifying and repairing components, coordinating routines and flexibilities across multiple systems, and engaging stakeholders to redesign systems over time, should be institutionalized in infrastructure-related organizations.

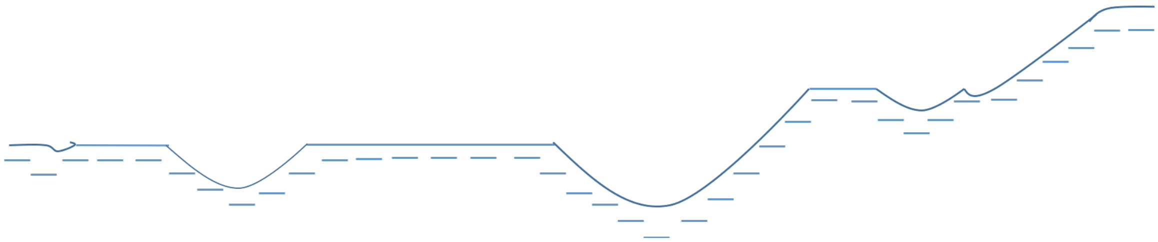

Figure 8. The adaptive curve comprises multiple short-term stabilities (source: Changdeok Gim, author)

4.6 The Functional Dynamics of Institutions: Sustaining, Adapting, and Transforming

The relationship between stable routines of organizations and their ability to adapt to uncertainties has long been discussed by many scholars (Rochlin et al., 1987; Robert, 1990). It is well-known that adaptive flexibility is the necessary complement to the stability of routinized procedures in supporting institutions and organizations (Craig et al., 2017; Beunen, Patterson, & van Assche, 2017; Denniz, 2016). Incessant subtle, adaptive, and innovative *processes* tempering uncertain social and environmental risks comprise multiple short-term rigorous engineering assessments for stability, *products.* How can an organizational reconciliation between stability and flexibility be achieved?

Academic efforts were made to investigate how formal and informal (Kunneke & Groenewegen, 2009) or the macro-level, meso-level, and micro-level (Bolton & Foxton, 2010) institutions can arrange, prompt, stymie, destabilize, co-evolve with certain technological developments, and also cause the obduracy of infrastructural lock-in (Hughes, 1983; Chester & Allenby, 2018). However, there has been little discussion on how both the stability and adaptiveness of institutions and infrastructure can be realistically orchestrated using different resilience concepts and time scales.

Technical stability sustains a system's function based on rigorous risk assessments and institutional strategies (e.g., preventive management, redundancy, and rehabilitation) aimed for short-term (day to year) outcomes. Institutional adjustments (adaptation) (e.g., the amendment of regulations) pursue appropriate responses towards alternative status quos with the mid-term (e.g., year to decade) replacement and reconfiguration of infrastructure. Social transformation as a form of long-term resilience is occasionally necessary to overcome unprecedented uncertainties. ‘Black swans’ have no reliable precedent data to reference, and thus no routine adaptations (Taleb, 2007; Katz, 2010) are possible. Institutions enable social and political transformation of a long-term duration (decade to decades) (IPCC 2014, p. 27). As institutions for sociotechnical material, infrastructure must be conceptualized with an epistemic recognition of temporal scales (**Fig. 9**).

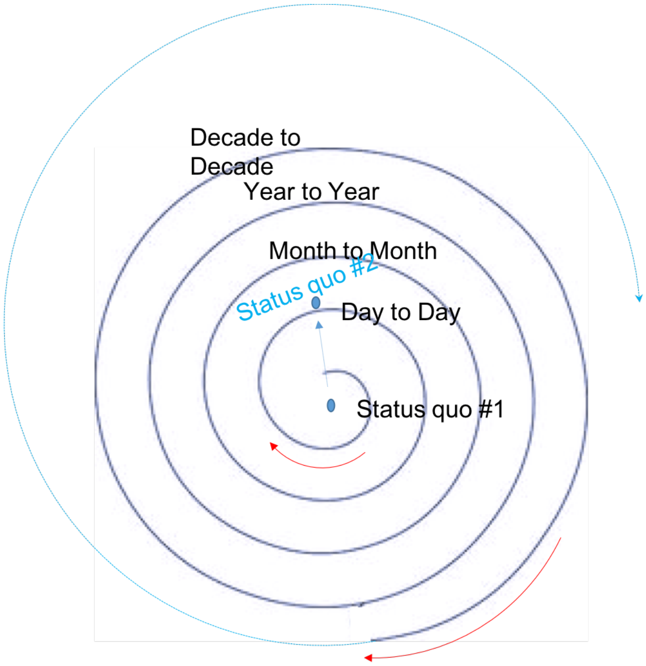

Figure 9. Resilience work spiral* (source: Changdeok Gim, author)

*The present status-quo #1 of infrastructure can move to a new constitutional, regulatory and operational status-quo #2 while adapting to environments for system resilience. This constitutional shift formalizes a different trajectory of regulatory circle (adaptive reconfiguration) and in turn new protocols (redundancy or preventive management) for physical sub-components.

One more caveat with institutional dynamics is that solid stability also includes hourly or daily minute adaptive *processes*, and *vice versa*. A short-term stability state at any divided moment should experience multiple subtle adaptions. Also, these adaptations and transformations should essentially end up with temporary, alternative stable states. The complementarity between stability and flexibility is not linear, but more compounded and concurrent via institutions. A technical stability at any given moment is not a static, but rather a socially agreed-upon "physical reality" induced from limited observed data (Sarewitz & Pielke, 2000).

4.7 The Resilience Work of Operational, Regulatory, and Constitutional Institutions

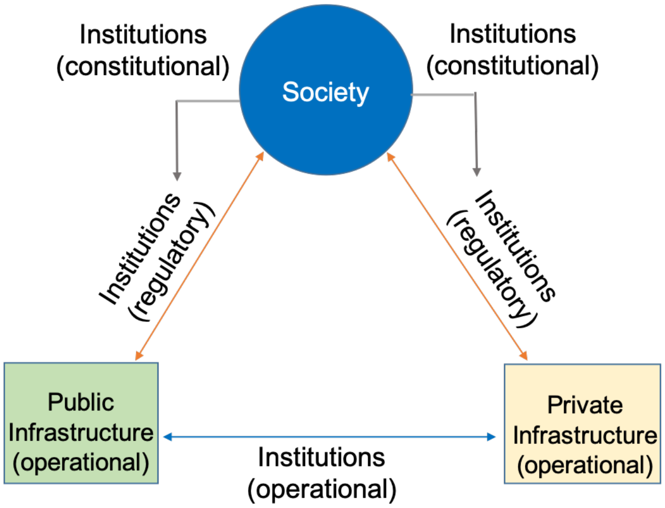

Figure 10. Types of functions of institutions (source: Changdeok Gim, author)

* Arrows depict the directions of institutional interactions between entities such as society and infrastructure.

Fig. 11 describes how institutions at different temporalities work and coordinate with different dimensions. In the following sections, based on **Fig. 11**, detailed work of institutions for infrastructure resilience will be investigated. In addition, how institutions sustain, update, and transform infrastructure will be analyzed based on institutional mapping of water and energy systems in Arizona.

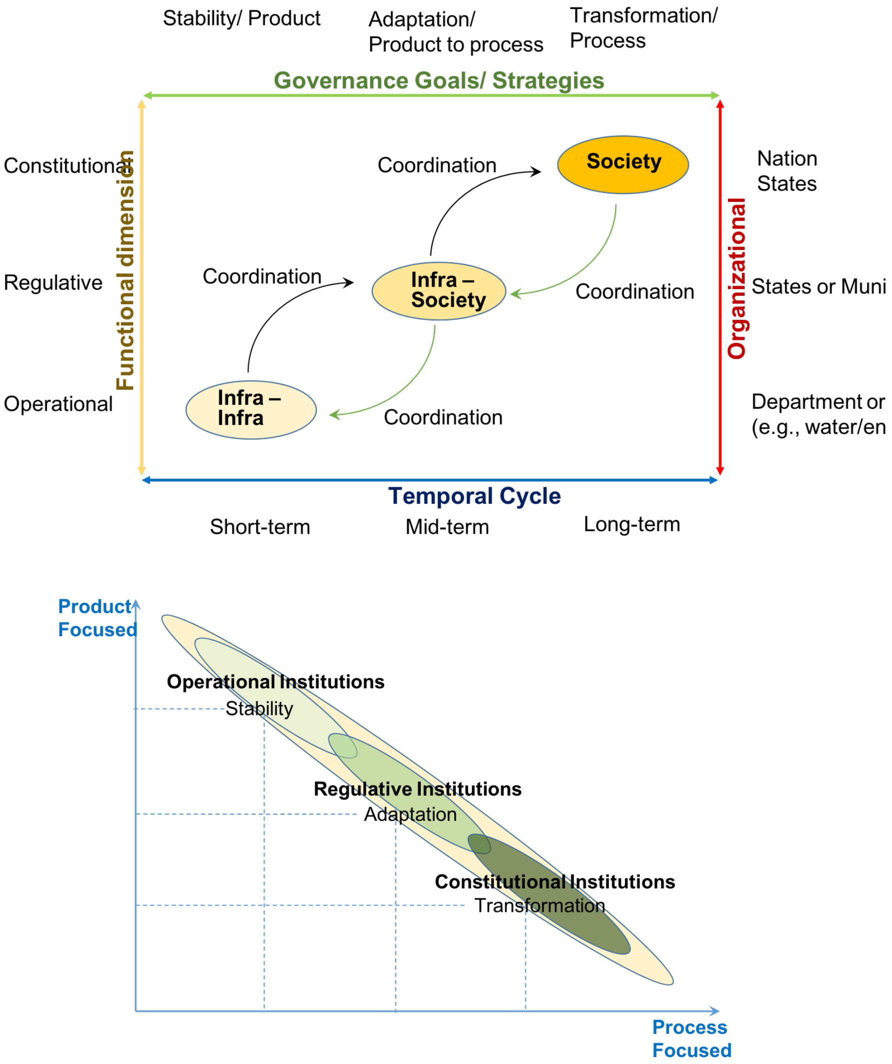

Figure 11. The topology of resilience work of institutions

(source: Changdeok Gim, author)

Resilience work by different types of institutions is analyzed in accordance with the framework in **Fig. 10**. Social systems (e.g., families, social groups, companies, local governments, and nation-states) and institutions that govern organizations of people have multi-dimensional structures (Holling, 2001). **Operational**, **regulatory**, and **constitutional** institutions contribute to multi-dimensional resilience of infrastructure (**Table 3**). The next section explores the dynamic nature of resilience work by institutions for infrastructure.

Table 3. Resilience work by different types of institutions (source: author)

Dimensions **Types of Institutions**	Temporal and Spatial Scales	Functional Dimension	Governance Goal	Uncertainties	Organizational Levels	Resilience Frameworks
Operational	Short-term: minutes to months Scale of discrete infrastructures	Sustaining systems operations	Resilience of engineered systems	Technical uncertainties in current or future systems performance, within clear engineering boundaries	Utilities and organizations that manage discrete infrastructures	Engineering resilience (Pimm, 1984; Holling, 1996), safe-to-fail (Ahern, 2011), green infrastructure (Sutton-Grier et al., 2015)
Regulatory	Medium-term: months to years Regulated entities and regulatory	Adapting systems through incremental adjustments	Resilience of socio-eco-technical systems	Uncertainties in complex systems interactions during disturbance and recovery, within clear regulatory boundaries	Government agencies and/or other regulatory entities	Ecological resilience (Holling, 1973), social-ecological systems robustness analysis (Martin-Breen

	jurisdictions					and Anderies, 2011), resilience engineering (Hollnagel, 2011 a; 2011b)
Constitutional	Long-term: years to decades Constitutional jurisdictions	Transforming systems into novel forms	Resilience of societies	Uncertainties in social and political dynamics with unclear boundaries	Society-wide constitutional bodies (e.g., legislatures, supreme courts)	General resilience (Walker & Salt, 2006)

4.7.1 Operational

Infrastructure-related institutions can be broadly divided into three types according to their functions: operational, regulative, and constitutional institutions. **Operational institutions** pursue the **stability** of systems in favor of **engineering resilience.** "Institutional structures and other factors combine to create at least short-term stability in the real world" (Niemi, 1983, p.269). Other factors here are largely recognized as institutional inertia, institutional interdependence, transaction costs, accountable outcomes, limited alternatives, and constraints on agenda (Niemi, 1983; Beunen, Patterson, & Assched, 2017; Lindner, 2003).

Operational institutions are responsible for **stabilizing** sociotechnical infrastructure, including cooperating with other organizations that operate and maintain related subcomponents. An **operational organization** (e.g., energy utilities) typically operates and manages physical infrastructure adhering to internal and external confirmed protocols and manuals for stable outcomes. For instance, utilities **maintain** the consistency of physical performance of infrastructure according to fixed standards. Operational institutions posit a steady state and pursue “a single steady or cyclic state” (Peterson et al., 1998, p.10) of patterns of human behaviors. Operational institutions support rapid cyclic returns of a system to this single state. **Sustaining** (**minute adaptation**) for stability is the resilience work of operational institutions, which has an inclination towards **stability** strategies and **single equilibrium**.

However, sustaining the resilience of infrastructure requires regular maintenance and periodic rehabilitation, both of which constitute a plethora of minimal adjustments. Short-term social and environmental changes (e.g., daily temperature changes, traffic flows, electricity demands, yearly updated reserve margin for summer season etc.) require infrastructural adjustment for adequate operation within a normal distribution curve. The stable performance (*product*) of infrastructure results from constant adjustments and daily optimizations pursuant to protocols established by engineering designers. In terms of the pre-shock status-quo in **Fig. 12**-(a), engineering resilience posits a normal state of infrastructure as flat as in **Fig. 12**-(a). However, **Fig. 12**-(b) reveals that the normal condition of infrastructure before shocks, which are represented as flat in **Fig. 12**-(a), is not *static*, but comprises dynamic activities with maintenance and rehabilitation works for infrastructure stability. In order to sustain the ‘flat’ mode of infrastructure while sustaining performance, infrastructure is in constant need of preventive maintenance, and light or heavy rehabilitation. The stable performance (*product*) of infrastructure results from incessant institutional adjustments and daily optimizations pursuant to protocols and standards confirmed by utilities. “[The] ‘maintenance’ of existing institutions often requires active and ongoing effort to uphold and defending existing institutions” (Beunen et al., 2017, p.12).

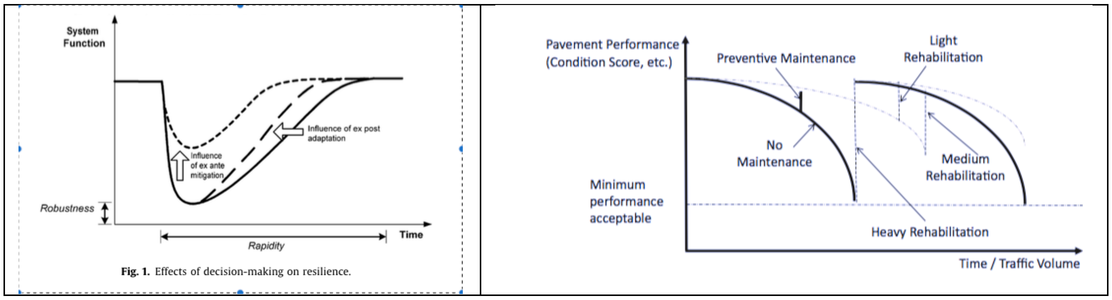

Figure 12. (a) Engineering resilience curve and **(b)** sustaining pavement performance by engineering maintenance (Mcdaniel et al., 2013; France-Mensach et al., 2018, p.3)

4.7.2 Regulatory

Regulatory institutions allow **the adaptation** (or correction) of infrastructural paths through robustness strategies. Robustness adaptiveness via regulatory institutions is not stability, which focuses on a single equilibrium, and thus proposes multiple desirable status-quos despite a clearly defined system boundary (Martin-Breen & Andreies, 2011; Anderies et al., 2013; Capano & Woo, 2017).

Infrastructure adapts to changing social needs via **incremental regulatory adaptation**. **Adaptation**, in other words, means path corrections. Systems need path corrections to sustain their performance capacity. Most regulatory policies use tools such as mandates, incentives, and sanctions to enhance the safety and resilience of infrastructure, or to correct market failures (e.g., monopolies, externalities, information asymmetry, and insufficient provision of public goods), or to improve distributional justice (Ouchi, 1980; Baldwin & Cave, 1999). The judicial branch, in the US, interprets legislative intent, confirms regulatory authority, and resolves disputes. Engineering protocols for water and power infrastructure are shaped by and must conform to these regulative standards established by social contract. Robustness, which means adaptive capacity to external shocks, is "**a property** of the institutional arrangements through which a system can adapt or can regain stability after having encountered periods of uncertainty and/or transformation" (Capano & Woo, 2017; Martin-Breen & Andreies, 2011).

Adaptation is also "**a process** through which an actor is able to reflect upon and enact changes in those practices and underlying institutions… (Pelling, 2011, p.39)," or "**the process** of adjustment to actual expected climate and its effects (IPCC, 2014, p.118)," 'Resilience engineering' regards these adaptive processes of proactive learning as a strategy to escape from "getting stuck in outdated approaches" to system problems (Woods, 2016, p.3). Social negotiations are inevitable features of adaptive processes for adaptations. Organizations and stakeholders make knowledge claims and negotiations about standards and facility or performance requirements for knowledge co-production (Miller & Muñoz-Erickson, 2018; Münoz-Erickson et al., 2017). Thus, corrections for adaptation, in most cases, hinge as much on right procedures and procedural justice as they do on scientific rigorousness.

When there are infrastructural failures or excessive stressors, or unacceptable social outcomes regulatory organizations seek to **replace** outdated standards with a new sociotechnical equilibrium. To implement these regulations, regulatory organizations **reconfigure** incentives and sanctions to organizations that operate critical infrastructure through a wide array of strategies.

4.7.3 Constitutional

Constitutional institutions structure particular sociotechnical systems and provide ground rules for operational protocols and sociotechnical regulations. **Transformational** adaptation through constitutional institutions arises in larger scales and longer periods (Folke et al., 2010; Martin-Breen & Anderies, 2011) than adaptations.

Constitutional institutions comprise political and legal consensuses, cultural beliefs, and sociotechnical imaginaries ("collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects," per Jasanoff and Kim, 2009, p.120). Over time, society translates norms, beliefs, and civic epistemologies into a fixed type of 'knowledge-order' (Jasanoff, 2005; Miller, 2007) such as constitutional law and Supreme Court decisions. This constitutional arrangement is the foundation by which regulatory institutions set specific standards, requirements, processes, goals, values, and authorities for decades.

The transformation of constitutional institutions towards "a fundamentally new system" emerges "when ecological, social, economic, and political conditions make the existing system untenable" (Walker and Salt, 2006, p.62). Constitutional transformation makes "a change in the fundamental attributes of natural and human systems" (IPCC, 2014, p.128). Transformational changes in society should be implemented or emergent "at a much larger scale or intensity," "[as] truly new to a particular region or resource system," and "[to] transform places and shift locations" (Kates et al., 2012, p.7156). Contrary to adaptive robustness frameworks, which are characterized by a defined system, a relatively short time period, and fixed variables, transformation has different properties such as **fundamental changes, uncertainties, a longer time period**, and **larger scales** of system transformation (Walker & Salt, 2006; Martin-Breen & Andreies, 2011).

Transformation is a **process-based approach** that is deeply rooted in complexity and uncertainties about the interplay between science and society. Sociotechnical transformations better fit **general resilience** frameworks than infrastructure resilience frameworks in part because science is not effective at long-term predictions in systems with unstable variables (Walker & Salt 2006; Folke et al., 2010). Social complexity greatly complicates our ability to forecast future conditions, needs, and preferences (Sarewitz & Pielke, 2000).

4.8 Sociotechnical Interdependencies

Infrastructure networks, such as water, energy, transportation, and communication are interdependent (Alderson & Doyle, 2010). The growing emphasis in engineering research and resilience policy on the interdependence of multiple infrastructure systems—such as water, energy, and transportation networks—tends to emphasize technological or physical interdependencies that create the possibility for failures to cascade across systems. A water shortage, for example, can impact the supply of water for cooling generators in thermoelectric power plants (Vliet et al. 2012). Electricity outages, in turn, can impede the delivery and treatment of water, halt the operation of rail and traffic signal systems, or prevent the supply of gasoline and natural gas for transportation (Rinaldi et al. 2001; O'Rourke 2007). Also, energy systems are dependent on transportation systems for the provision of fossil fuels and workforce. Communication facilities and services are the key elements for managing processes of work field in water and energy systems. These complex interdependencies are increasingly understood to give rise to emergent and unpredictable behaviors through their interactions (Holland and Miller 1991, p. 365) that exacerbate vulnerabilities to a greater degree than would occur within relatively more simple systems (Alderson and Doyle 2010).

These kinds of physical interdependencies of infrastructure have been studied as a source of vulnerabilities and a challenge for efforts to make infrastructure more resilient to climate disruptions. The effects of climate extremes (e.g., droughts, storms, floods, and blizzards) on physical networks are projected to exacerbate the vulnerability of interdependent infrastructures (Hunt & Watkiss, 2011, p.26). Electricity outages can shut down water pumps, either causing shortages in water distribution systems or floods due to wastewater pump failures (e.g., the city of San Diego case). Disturbances and technical failures in water systems may propagate through physical linkages between the water and energy systems and in turn affect the function of power systems. For instance, high temperatures have forced nuclear power plants to shut down temporally in Europe (2018) and in the state of Tennessee in the United States (U.S.) (2011) (Hersher, NPR, Jul. 27, 2018; Linnerud, Mideksa & Eskeland, 2011). Environmental regulations ban nuclear reactors from adding heat to riverine or oceanic water with their discharged hot water. More significantly, the shortage of cooling water in crisis can cause devastating failures as seen in multiple cases, such as Three Mile Island and Fukushima nuclear accidents.

To understand infrastructure vulnerabilities and resiliencies, the analyses and reconfiguration of the dynamics of institutional processes are necessary, which include monitoring the functioning of systems, coordinating routines and crisis responses across multiple systems, identifying and repairing systems components, and redesigning constitutions over time in response to a variety of changes to the system and its contextual environment.

Therefore, this chapter proposes to expand on this understanding of infrastructure resilience by examining another form of interdependence that is not physical but rather enmeshed in institutional and social network linkages among and across infrastructures. A number of studies have begun to explore non-physical interdependencies and their impacts on resilience. For instance, a recent study argued that regulatory failures due to close ties between operators and regulators contributed to the Fukushima nuclear disaster (Kurokawa & Ninomiya, 2018). The unsound relationship between the Japanese government, the regulatory agency (NISA), and the Tokyo Electric Power Company (TEPCO) caused an institutional vulnerability, *regulatory capture,* and this regulatory failure ultimately led to the Fukushima disaster in 2011: "the root causes were the organizational and regulatory systems that supported faulty rationales for decisions and actions" ("The Fukushima," 2012, p.16). *Logical* (Rinaldi et al., 2001) and *invisible* networks of social elements (Edwards, 2003; Anderies, 2013) often prove to be critical points for recovery and adaptation of systems after disruptive events in spreading networks. Well-informed decision making (McDaniels et al., 2008) and sophisticated organizational interdependence (Thompson, 1967) can better equip infrastructure to sustain, adapt, and transform arrangements and functionality.

Building on this preliminary work, this chapter develops a more generalizable approach for defining, identifying, and analyzing institutional interdependencies in infrastructure systems. Section 4.9 of this chapter defines and describes different types of institutional interdependencies of infrastructure from the perspective of systems theory.

4.9 Institutional Interdependence and Infrastructure Resilience

Approaching infrastructures as systems, and especially as sociotechnical systems, which integrate social, economic, and institutional dynamics with engineered technologies, changes the analysis of infrastructure resilience. In open, sociotechnical systems, properties or functionalities of infrastructures, such as their dependability or resilience, are emergent phenomena that arise from complex interactions between social and technical aspects (Emery & Trist, 1960; Mumford, 2006; Baxter & Sommerville, 2011). In physically interdependent infrastructures, vulnerabilities and failures are well known to emerge from complex and tightly coupled component failures (Perrow, 1984) and propagate within and across systems due to physical interdependencies (see, e.g., **Fig. 13**). In sociotechnical systems, vulnerabilities also arise from social elements of the system and can travel from system to system along with social and institutional pathways (Silva et al., 2012; Chappin & Lei, 2014). When compared to the static engineering analysis of the water and energy nexus, institutional networks also experience more complicated and dynamic forms of interdependence. The resilience of infrastructure to climate change thus must be assessed in terms of complex, sociotechnical systems dynamics, including not just engineering but also ecosystems, economic, policial, health, and bureaucratic elements (Bertalanffy, 1972; Senge, 1990; Seager et al., 2013; Grabowski et al., 2017).

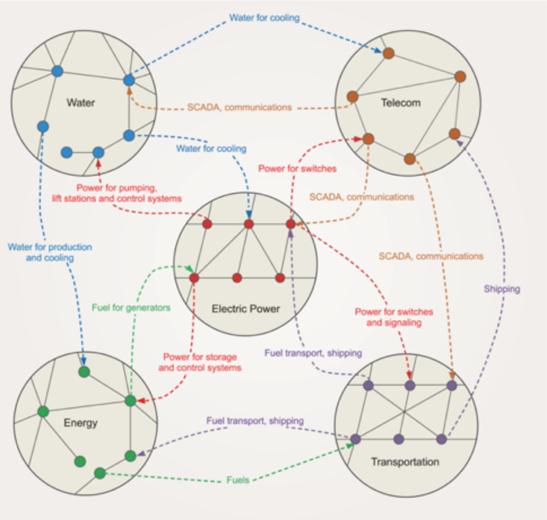

Fig. 13 From a single system to interconnected systems (Rinaldi et al., 2011).

This chapter is particularly concerned with the institutional arrangements and elements of sociotechnical systems that contribute to exacerbating the vulnerabilities of tightly coupled infrastructures (Alderson & Doyle, 2010; Rinaldi et al., 2001; O'Rourke, 2007). Recent studies have highlighted the importance of institutional anticipations and governance structure in response to endogenous and exogenous instabilities (de Bruijne and Herder, 2009; Bollinger, L. et al., 2014; Chappin & Lei, 2014). These studies have not yet, however, focused in depth on institutional interdependence across systems.

To analyze the contribution of institutions to infrastructure vulnerability and resilience requires extending sociotechnical systems theory from single systems (e.g., the electricity grid, see Hughes 1983, or coal mining, see the UK Tavistock Institute, Emery & Trist, 1960) to complex, interdependent systems. This is consistent with other recent trends in the study of organizations, which are "moving away from hierarchies to networks (Castells, 1996) and from centralized to decentralized structures in which parts of a company are run as semi-autonomous units" (Mumford, 2006, p. 335). It is also consistent with emerging approaches to the study of resilience in engineering and organizations that recognize that resilience is a dynamic property of socially and institutionally managed systems and that the enhancement of resilience requires careful attention to the dynamic practices and processes through which resilience is achieved through vigilant learning and feedback (e.g., via sensing, anticipating, adapting, and learning, see Hollnagel, 2011; Park et al., 2013; Linnenluecke et al., 2011; O'Rourke, 2007).

Institutional interdependence is defined as *the reciprocal connections among different infrastructures which interact through institutional processes, practices, and rules such as operational protocols, regulatory policies, and laws*. Interdependent networks rely on constant regulating, intervening, cooperating, and exchanging of resources in systems (Thompson, 1964). Such collaborations and interventions take place and are governed by institutions. Institutions manage the collection, interpretation, and use of data to assess risks, such as climate change, and to identify and evaluate responses. They operate infrastructures, including regular management of technology (e.g., water levels behind storage dams on river systems), options designed to enhance resilience (such as the opening of flood gates to relieve high water levels, see ASCE 2007; Park et al., 2013), and the performance (or failure to perform) routine maintenance. Institutions are also regulated—and regulate one another—in tightly interdependent, multi-centric governance arrangements that include operational entities, regulatory bodies, and legislative and constitutional institutions. In worst case scenarios, these institutional configurations readily become pathways for vulnerabilities which propagate through various institutional links and nodes while threatening the reliability and dependability of these systems.

Institutions also inevitably face decision making trade-offs (e.g., between infrastructure performance and ecosystem services) in their efforts to improve the resilience of both individual as well as interdependent infrastructures (Brown, Tompkins, & Adger, 2001; Janssen, 2007; George, 2014). Trade-offs that enhance the robustness of one system (e.g., the protection of groundwater) while constraining the performance of other systems (e.g., the expansion of thermoelectric electricity systems) (Janssen, 2007) also occur across a variety of forms of institutional interdependence, such as financing, eminent domain, social sabotage, labor negotiation, etc. Interdependent institutions are thus loci wherein *losers* and *winners* (Smith & Stirling, 2010) convene and negotiate for the right institutional design of trade-offs in sociotechnical contexts. Central questions for infrastructure resilience analyses are therefore how, specifically, any given set of complex infrastructure systems are interconnected, institutionally and organizationally, via webs of institutional interdependencies, how these webs propagate vulnerabilities or failures or, by contrast, strengthen and support resilience, and how institutions choose to manage institutional interdependence. A recent study of community resilience to Hurricanes Irma and Maria in Puerto Rico similarly observes, for example, that vulnerabilities to climate change flow through diverse social and institutional pathways (Eakin, Muñoz-Erickson & Lemos, 2018).

4.10 Institutional Conduits for Trade-offs and Two Types of Institutional Interdependencies

4.10.1 Trade-offs and institutional threads

One more important point of institutional analysis is related to trade-off threads on values and resources. Trade-offs on different values and resources run through all three elements of vertical, lateral, and longitudinal institutional venues (threads). Pooled resources shared by stakeholders condition trade-off dynamics, where infrastructural interdependencies reside and solidify. For example:

i) The vertical structure of institutional connections brings trade-off decisions including the power dynamics of directive guidance, devolution, and feedback between central groups and administrative sub-groups. Vertical trade-offs occasionally entail unilateral, institutional decision making such as the destruction of sub-organizations so that the greater systems can thrive (Janssen, 2007). Global adaptations and sustainability frequently require local sacrifice in the vertical threads of organizations (Woods, 2011).

Therefore, vertical trade-offs are typically sequential rather than reciprocal across hierarchical levels, although this is rarely complete. For instance, the headquarters of corporations typically audit and allocate resources to sub-groups within the same group via institutional directions.

ii) Trade-offs cross and flow through lateral institutional threads while facilitating the exchange of opportunities among infrastructures (Gunderson & Holling, 2002). The hierarchical direction from upper-level organizations can prompt the exchange of opportunities in lateral domains. Direct regulations on CO_2 emissions by the EPA can impose a financial burden on fossil fuel power utilities, and this constraint indirectly creates a lateral swap of capital investment towards new industry sectors (renewable energy and electric car manufacturers). Constraints and opportunities cross over to myriad, interdependent combinations via vertical and lateral networks across infrastructures. By virtue of releasing resources from one system, the other system can reorganize its structure and conserve outcomes (Gunderson & Holling, 2002) and these circulations are materialized via lateral linkages. Specifically, in traffic systems, operators observe and continuously switch traffic signal intervals for managing capacity trade-offs between roads depending on daily traffic.

iii) Trade-offs also arise alongside longitudinal continuities of institutions over time. Different stakeholders at different time periods are legally bound via the continuation of laws and regulations. Fossil fuel systems contributing to historical accumulations of CO_2 emissions, supported by laws and regulations, face transformational system challenges and financial burdens for clean energy in a new era. Updating institutions need consideration on generation gaps in energy cultures and the time discrepancies of CO_2 emitters and greenhouse gas regulators to overcome the remnants of fossil fuel systems (Gardiner, S. M. & Hartzell-Nichols, L., 2012). Infrastructure aging is also a longitudinal, institutional trade-off challenge to both contemporary taxpayers and future beneficiaries, which is nurtured by the continuity of certain tax laws. Evenly spreading of benefits and burdens across longitudinally different taxpayers within the same infrastructure community is a fundamental question to the sustainability of infrastructure.

4.10.2 Two types of interdependencies

The implication of the analysis on institutional threads and trade-offs via institutions is that two-types of institutional interdependencies enfolding infrastructures can be found: direct or indirect interdependence. The infrastructure management of one system can directly or indirectly affect the operation and management of the other systems (**Fig. 14**). First, an institution of one system directly regulates the operation and management of the counterpart system via hierarchical threads. In this case, direct institutional interdependence postures tighter connections between two different infrastructures. For instance, institutional governance of water systems on using groundwater regulates electricity utilities in Arizona. A groundwater aquifer is a component of the water resource system and has been regulated by state-level water institutions in Arizona. If groundwater regulations change, then the operation and management for the usage of groundwater by power plants must by necessity change as well. In some cases, water security is privileged over electricity robustness in a way that sacrifices electricity expansion in exchange for the sustainability of Arizona's whole social-ecological system. The direct intervention via a vertical thread from the water system represents a value emphasis on water at the expense of upgrading energy capacity.

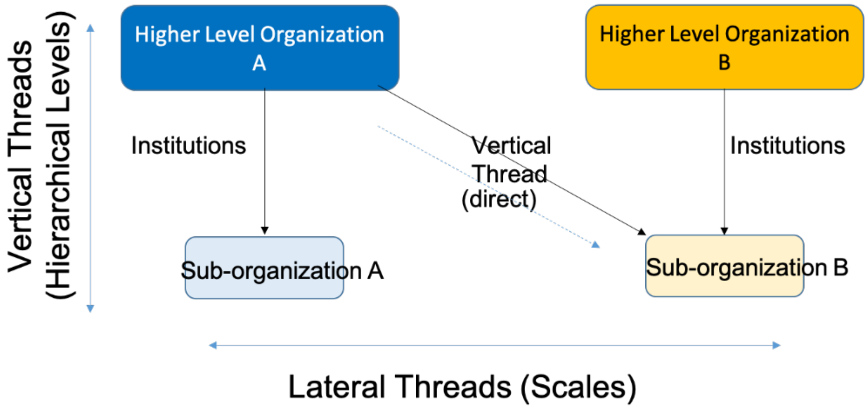

Figure 14. Direct interdependence (source: Changdeok Gim, author)

Second, with respect to indirect intervention, interdependence can occur via hierarchical and lateral threads between different infrastructures (**Fig. 15**). Indirect interdependence includes one system's institutional changes vertically maneuvering the codes or standards of sub-organizations, and, via lateral linkages, these changes indirectly affect the counter system's operation and management. For instance, the operational planning of water-related organizations can be modified in accordance with changes in higher-level organizational governance derived from environmental challenges, and then these institutional changes can affect, via institutional and social linkages, the provision of water resources to the electricity utilities that operate power plants. The operational changes in electricity utilities, which regulate the operation of power plants, are not associated with any direct interventions of decision making from higher-level organizations in water systems.

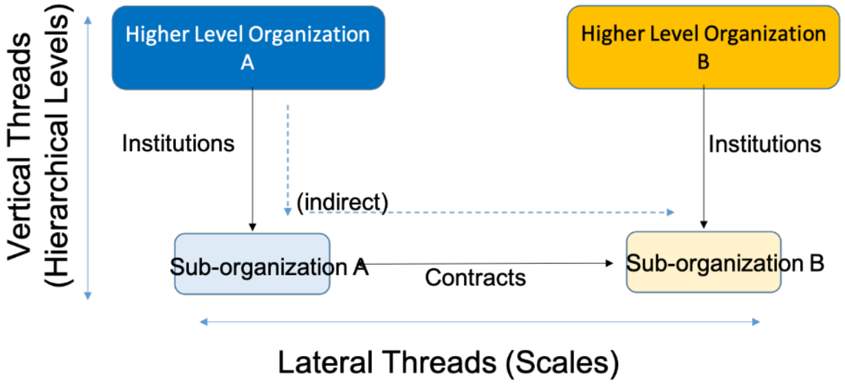

Figure 15. Indirect interdependence (source: Changdeok Gim, author)

4.11 Conclusion

Infrastructure resilience means stability in the short-term as well as transformability in the long-term. Thus, an institutional approach critical to infrastructure resilience emphasizes how a system sustains, adaptively adjusts, and innovatively transforms, when necessary, its structure and function via institutions in a strategic way. The essential element of infrastructure resilience should not be simply conceived of as equivalent to a fast bounce back to the original state after disturbances. Rather, an institutional balance between engineering stability and social transformability (Beunen, Patterson, & van Assche, 2017) at different temporal scales should be a crucial feature of infrastructure resilience.

Furthermore, infrastructures are not only physically, but also institutionally interdependent, and thus analyses of institutional interdependence are essential for systems resilience. External disruptions, not necessarily in the form of physical disruptions, flow through institutional networks. Climate change runs through institutions while influencing institutional contexts for water and energy systems in Arizona. The investigation on institutional interdependence clarifies institutional threats that water and energy systems will face and need to overcome in response to climate change. As such, climate stressors to infrastructure are also challenges to institutional interdependence of infrastructure. Society, technology, and environmental disruptions interact through institutional webs. Discussion on the strategic adaptation of interdependent infrastructure considering local institutional attributes is essential. Broad engineering quantification without looking at local institutional traits is parochial. Circumscribed abstraction of physical realities and the exclusion of institutional interdependence can lead to misdirected validation of knowledge and fallible policies (e.g., naïve resilience tactics and strategies).

Chapter 5 examines the institutional management of Hoover Dam and its resources—water and electricity—to illustrate how society and institutions have shaped this critical infrastructure while focusing on the allocation of common pool resources. Hoover Dam was constructed by myriad technological acts and assessments, but the infrastructural utility and operational functionality for service were all arranged by institutions, which is imperative to the sustainability and resilience of infrastructures (e.g., Hoover Dam) in society (Bijker, Hughes, and Pinch, 1987).

CHAPTER 5

A CASE STUDY OF INFRASTRUCTURE AS A SOCIOTECHNICAL SYSTEM: WATER AND ELECTRICITY FROM HOOVER DAM

5.1 Introduction

The first four chapters of the dissertation have laid out the theoretical argument that institutional work is an integral element in the resilience of critical infrastructure systems. This theoretical argument has developed around three key ideas. First, in Chapter 2, the dissertation introduced the idea of defining and describing infrastructure in terms of sociotechnical systems, i.e., that infrastructures have interlinked social and technical elements that interact dynamically with one another to form the infrastructure system. Second, Chapter 3 discusses the multiple definitions of resilience and argues for redefining resilience as a dynamic property of socio-technical systems, rather than a static property of engineered systems, in which institutional work provides the capacity to create both short-term stability and long-term flexibility. Finally, Chapter 4 delves deeper into the role of institutions in managing resilience, establishing a broad framework for mapping and classifying the resilience work of institutions and for analyzing the institutional interdependencies associated with complex infrastructure systems.

Building on this theoretical work, Chapters 5-9 present empirical analyses of different aspects of the institutional dimensions and work of resilience. These analyses are grounded in multiple case studies of energy and water systems in Arizona. In each chapter, one or more case studies is used to demonstrate a key aspect of how resilience work plays out in practice in the work of one or more institutions.

The purpose of Chapter 5 is to illustrate the core argument of Chapter 2: infrastructures are not just engineered systems but sociotechnical systems. Thus, the work of building and operating those infrastructures is not just engineering work but also social, political, legal, and institutional work. Chapter 5 is particularly concerned with one of the central infrastructures of the Arizona water and energy systems, Hoover Dam, a water storage dam with hydroelectric generating capacity built in the 1930s and 1940s as the lynchpin of efforts to develop the water and energy resources of the Southwest region. The chapter shows that, in order to make it possible to build the dam, as a technological object, the US government first had to establish a legal or constitutional basis for its existence. This included both settling major political conflicts about water ownership, e.g., via the 1922 Colorado River Compact, and creating a legal basis for federal ownership and operation of electricity generation and sales, e.g., via the 1929 Boulder Canyon Project Act. Put theoretically, Hoover Dam was co-produced with its institutional and legal constitution.

This system has not stayed static, however. Rather, institutional work has continued long after the construction of the dam in order to periodically update the regulatory arrangements for allocating water and electricity among diverse users. These adaptations have been necessary in order to adjust the operation of the dam in response to changes in both political values and social dynamics as well as the behavior of the physical systems involved. Several constitutional changes have occurred over the years, including the integration of Arizona into the legal agreements for water and power allocation, the reconfiguration of rights to water and power around the Southwest Native American communities, and the persistent drought in the Colorado River watershed since the 1990s. Chapter 5 thus also illustrates the idea of constitutional resilience work, helping to maintain system functionality through transformational change in the supply of water and electricity over time in the Southwest.

5.2 The First Electricity Transmission (from Hoover Dam to Los Angeles)

On October 9th, 1936, the first transmission of electricity generated from the turbines of Hoover Dam began (**Fig. 16**). This transmission system spanned 266 miles across the area of mountains and deserts and arrived at the Civic Center of Los Angeles. With a flash, lightning started at 7:36 pm on Friday night. On Friday night, the parade started at 8:00 pm with “an illumination of 7,000,000,000 candlepower” and next day the Electrical Age Exposition was held in Pan-Pacific Auditorium. The parade with thousands of marchers illuminated by rainbow flash started at Washington Boulevard, moved to First Street, and went down the street before the Civic Center. At Sunset Boulevard, the parade ended (“City Waits New Power.” Los Angeles Times, Oct. 6th).

The guideline for the allocation of hydroelectric power from Hoover Dam was legislated by the US Congress in the Boulder Canyon Project Act of 1928 before construction was completed in 1935. Complying with the Boulder Canyon Project Act of 1928, the US Secretary of the Interior executed electricity allocation contracts on April

26th, 1930 and finished allocation for annual energy generated by Hoover Dam, about 4 billion kWh, in 1931. In 1934, Congress signed a 50-year contract that spanned from 1937 to 1987 that regulated the allocation of hydropower from Hoover Dam. The utilities purchasing that power and delivering it to their service territory, as defined in this act, were Southern California Edison and the Los Angeles Department of Water and Power.[2] The contract between the United States and the City of Los Angeles and its Department of Water and Power, and Southern California Edison Company, Ltd., "Contract for the Operation of Boulder Power Plant (No. I1r – 1333)," was made on May 29, 1941. Since this initial allocation of hydropower from Hoover Dam, there were two more developments with hydroelectricity allocation, in 1984 and in 2011 (The Bureau of Reclamation, 1980, p.57).

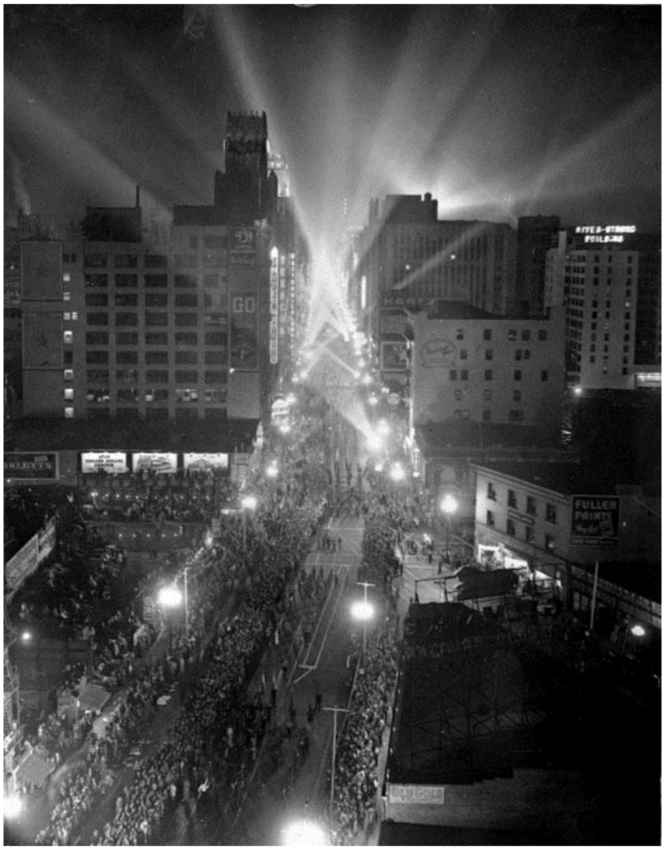

Figure 16. The first transmission*

(source: Water and Power Associates website:
https://waterandpower.org/museum/Construction_of_Hoover_Dam.html)

* People were crowded on the route in Broadway on October 9th, 1936. A myriad of lights glowed with the electricity transmitted from Hoover Dam power generator.

Given that Hoover Dam's hydropower is derived from a federally-owned facility releasing water from a public reservoir, the hydropower can be seen as a sort of common pool resource. Thus, to study the history and dynamics of hydroelectricity allocation in light of common pool resources is deemed important and relevant.

5.3 Governing Common Pool Resources from Hoover Dam

5.3.1 The application of common pool resource criteria

In Ostrom's book, the common pool resource is defined by two attributes: excludability and subtractability. Therefore, to apply Ostrom's theory to hydroelectricity from Hoover Dam, there have to be these two attributes. First, hydroelectricity can be generated only by the release of water from Lake Mead through Hoover Dam's power turbines. The water resource of Lake Mead can be blocked from external entities without entitlement of access to this resource. The abuse of this resource will be excluded. Without water resources, there is no hydroelectricity. Thus, the hydroelectricity has excludability. Second, the water resource of Lake Mead is subtractable which means the diversion of water from Lake Mead leads to the depletion of water resource-since the hydroelectricity cannot be generated without water release from Lake Mead. This results in insufficient water resource for the generation of hydroelectricity. Thus, hydroelectricity also has another attribute, subtractability for common pool resource.

5.3.2 The significance and details of the common pool resource criteria

Ostrom's idea is that the management of common pool resources leaning on the external authority sometimes results in inefficient or undesirable outcomes as observed in the empirical examples. Ostrom holds that self-governance as opposed to a command and control structure from outside the stakeholders and direct beneficiaries can be a more efficient and desirable management method. Thus, this system can be more sustainable than other systems. To understand Ostrom's common pool resource management approach, the following sections first begin with Garrett Hardin's "the tragedy of the commons." In this chapter, how the management of resources from Hoover Dam has been sustained and adapted by institutions will be investigated.

5.3.3 Garrett Hardin's "the tragedy of the commons"

Elinor Ostrom's idea is so different from that of Hardin that she denies the simple resolution upon external authorities such as government or market system. It is worth noting that before Ostrom postulated her theory, Garrett Hardin's pessimistic perspective concerning the improbability of successful self-governance for common pool resources had prevailed. As a microbiologist, Hardin had been interested in human overpopulation and sociobiology. Garrett Hardin's seminal article, "The Tragedy of the Commons," first focused on the problem of overpopulation for the sustainability on our planet (Hardin, 1968). He asserted that to ask people to have fewer children through "an appeal to conscience" would be a mistake. He further argued that this method would lead to the elimination of conscience from our society because those with a conscience would choose to limit their reproduction while those without a conscience would breed freely and become the majority. As a consequence, those whose behavior is based on conscience will become the minority. He extended this dilemma to explain the tragedy of the commons using the idea of a common pasture as an example. Assuming there is a pasture accessible to all herdsmen, we can expect all herdsmen try to breed as many cattle as possible on this common pasture. The following logic explains Hardin's paradigm: When a cattleman puts an extra cow on the commons, he can get the whole benefit of the value of the cow when he sells it. However, the loss in the forage available on the common pasture is shared among all the cattlemen who use the commons. In other words, the cattleman gets all the benefit of the extra cow but suffers only a small portion of the cost. Thus, all the cattlemen, if they are rational, will try to add extra cows to increase their profits, and the common pasture will be overexploited and eventually degraded. The incentive for profits leads to an unlimited increase in the number of cows.

Hardin suggests the National Parks as another example of the tragedy of the commons. As the number of people who visit the National Parks increases, the value of the natural landscape will diminish. For these tragedies, he proposes several options. First, he contends that we can divide our pasture or parks into several parts and make them private property, with the assumption that the owner of the pasture or park will regulate its use to avoid degradation. Alternatively, we can keep the pasture or park as public property, a common-pool resource, and allocate specific rights of use to specific members of the community. The decision making for who should be the members are diverse. There may be a lottery, an auction, or it could be a first-come and first-serve basis. So, both governmental authority (mutual coercion upon mutual agreement) and private property regimes with market-based allocations offer solutions to the tragedy of the commons, according to Hardin. He suggested that the government allocation and management of common pool resources can be effective if mutual coercion is based on mutual agreement and recognition of necessity. In other words, the users of the commons agree on a system of regulations to avoid the overuse of the commons. In his controversial conclusion, Hardin returned to the issue of overpopulation and argued that paradoxically the best way to preserve the freedom of reproduction is to mutually agree to limits on an individual's right to reproduce.

5.3.4 Governing common pool resources (Elinor Ostrom)

Elinor Ostrom asserted in her book, *Governing the Commons: The Evolution of Institutions for Collective Action*, that the common pool resource can be self-governed by a community. This assertion is contrary to the conventional analysis for common pool resources. The conventional analysis posited that it is inevitable that common pool resources will be depleted without government's regulation or a privatized market system under total privatization. Ostrom used examples of self-governing resources in diverse situations and nations. Ostrom's main idea was that public service such as operation and maintenance for common pool resources can be accomplished without government's organization or market system under several special conditions (Ostrom, 1997; Ostrom, 2011). Ostrom highlighted the limitation of external authorities as below:

> “ … I do not argue for either of these positions. Rather, I argue that both are too sweeping in their claims. … Institutions are rarely either private or public – “the market” or “the state.” Many successful CPR institutions are rich mixtures of “private – like” and “public – like” institutions defying classification in a sterile dichotomy. …” (Ostrom, 1997, p.14)

The logic of this perspective aims at overcoming the result of Prisoner’s Dilemma Game. This ‘collective action’ problem, which means that rational cooperation cannot be achieved among rational individuals seeking selfish advantages like Garrett Hardin’s (1968) idea. In the traditional framework for collective action, individuals are regarded as straightforward utility maximizers, and collective action readily leads to a social dilemma such as the under-provision of public goods. However, Ostrom’s contribution is to show the possibility that this bounded rationality can be overcome through building a ‘common pool governance’ structure.

5.3.5 The characteristics of the allocation of the hydroelectricity from Hoover Dam

There are two differences between Ostrom’s conceptiuon of a common pool resource and the hydroelectricity from Hoover Dam. First, the hydroelectricity from Hoover Dam needs the construction of Hoover Dam. This means for generation of hydroelectricity, there should be an investment of construction cost. Who will pay this cost is directly connected to the problem of who will benefit from the common infrastructure; that is, no dam, no hydroelectricity. Second, although Ostrom’s theory mentions the self-governing of common pool resource, the theory could not sufficiently accommodate the case of Lake Mead and Hoover Dam since Lake Mead and Hoover Dam are both under government's control. The government has the legal right of allocation of water and hydroelectricity. Even though hydroelectricity is a common pool resource, the allocation of hydroelectricity should be done by the government and the criteria for this allocation should consider the construction cost of Hoover Dam. Put simply, in the criteria for the allocation of hydroelectricity from a public dam, the common pool resource criteria and governmental allocation criteria can be put together simultaneously. Thus, deciding who will benefit from publicly owned infrastructure has two steps.

The first step is to figure out who has the willingness to pay the cost of the construction and the operation of the common infrastructure. The second step is to decide who will be the beneficiaries if the people who want the resource outnumber the capacity of the common infrastructure. In the first step, we can just follow the simple and succinct principle, "The user-pay principle." However, in the second step, a different rule should be established. This is because the purpose of the public infrastructure is to advance the public interest, not necessarily to pursue profit. Given the aspect of common pool resource in the allocation of hydroelectricity, it is convincing that the allocation of hydroelectricity has to follow the criteria of common pool resource. Therefore, it is needed to review the problem of who should benefit from the Hoover Dam's hydroelectricity in two different perspectives, namely willingness to pay and common pool resource criteria.

5.3.6 Ostrom’s eight conditions for the sustainable management of Hoover Dam

Among the sustainable conditions in Chapter 2, in this essay, the conditions (2), (3), (6), and (7) will first be the focus of the discussion regarding the management of Hoover Dam. Condition (1) is clear with the boundary of Lake Mead and the transmission lines. Conditions (4), (5) are accomplished by the federal legal systems such as civil law and criminal law. Condition (8) is not reviewed in this research because this research does not deal with the allocation of hydroelectricity in the sub-jurisdictions under the states.

With respect to the conditions (2), (3), and (7), the following sections will investigate what the guideline was used for the allocation. Also, these sections will examine how an agreement on the allocation of the Colorado River among the stakeholders (e.g., the states of California, Arizona, and Nevada) was made for the allocation of hydroelectricity. The hydroelectricity from Hoover Dam is bound with water from Lake Mead. Therefore, it is meaningful that by looking into the allocation of water, the collective-choice arrangement (rule-making)—according to Ostrom’s theory, collective-choice rule is connected to the policy making for the management of the common pool resources. How the common pool resources should be managed is directly related to this level of rule (Ostrom, 1990, p.52-53)—and the agents’ negotiation for mutual agreement about the allocation of hydroelectricity can be elaborated. In relation to the condition (6), the background, progress and resolution mechanism of the legal dispute as a conflict-resolution mechanism between the states of Arizona and California will be studied.

Second, for applying Ostrom's theory, the hydroelectricity has to come from the *publicly owned* dam which is *public* infrastructure. For this point, the social and economic backgrounds of the construction of the "public" Hoover Dam with the federal budget will be studied. With these focal points, we can review how the allocation of the hydroelectricity as a common pool resource was accomplished. The existence of public infrastructure, the collective-choice arrangement, the negotiation among the states for mutual agreement, and the dispute resolution mechanism will be discussed in this essay. This will make the discussion about common pool resources (infrastructures) deeper and applicable to society.

5.4 Sociotechnical Transformation for 'Public Hydroelectricity' at the federal level

5.4.1 A transformational support for the construction of Hoover Dam

5.4.1.1 The formation of the Boulder Canyon Project Act at the federal level

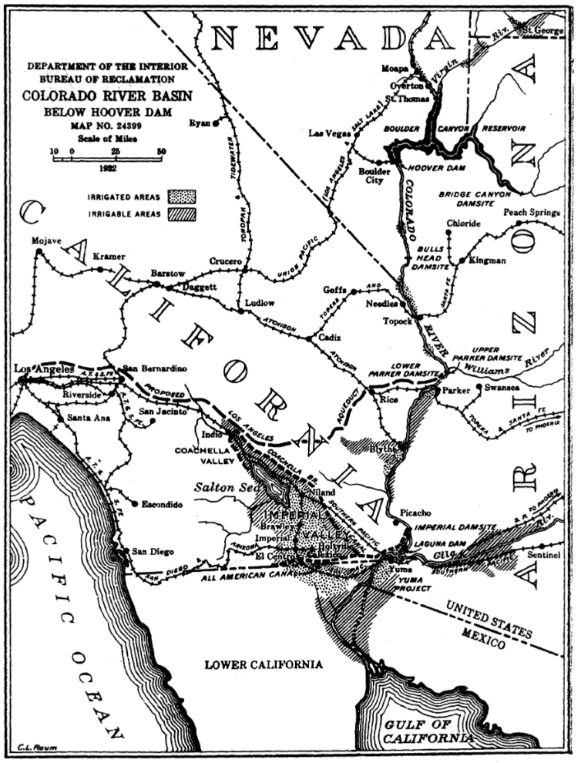

Figure 17. The Boulder Canyon Project and adjacent territory

(source: U.S. Department of the Interior, *The Hoover Dam Power and Water Contracts, 2*)

Major John Wesley Powell explored the Colorado River basin and documented his exploration in his report in 1878, “Report on the Lands of the Arid Region of the United States” (Worster, 1985, p.133). He stated that the essential component for the future of this area would be the storage of water. He suggested that Congress prepare and conduct a survey of irrigation opportunities. The dominant idea in his mind was that water in the West should be rationally managed to maximize its efficient use in a region of water scarcity. “It is of the most immediate and pressing importance that a general survey should be made for the purpose of determining the several areas which can thus be redeemed by irrigation" (Worster, 1985, p.134).

However, the survey was not conducted because Congress thought it would be useless. In 1907, the President of the United States, Theodore Roosevelt, recommended that Congress pass a law to protect the Imperial Valley in the state of California from flooding. Congress was still reluctant to authorize funding to build extensive reclamation projects in the Colorado River basin. Within ten years, Congress became more amenable to federal investment in the Colorado River basin. A report by the All-American Canal Board established by an agreement of 1918 became a trigger to develop the Imperial Valley irrigation system. In this report, the All-American Canal Board argued that a large storage reservoir should be constructed in the Colorado River basin. With this report, the first and the second All-American Canal bill were submitted to Congress in 1919 and 1920 consecutively. However, the bills were rejected on the ground that the data was not sufficient for validation. In 1920, the Kincaid Act required the Bureau of Reclamation to investigate the Imperial Valley area and the status of irrigation. On February 28, 1922, a report by Arthur Powell Davis, Reclamation's Director and Chief Engineer, was submitted to Congress. In his "Report on problems of Imperial Valley and vicinity," Arthur Powell Davis pointed out several significant investigation results for the development of the Boulder Canyon (Hiltzik, 2010, p.67; Linenberger, 2002, p.43). The most important point of them was that a storage reservoir should be constructed in the Boulder Canyon area and the construction cost funded by the federal budget and this cost be reimbursed by selling hydroelectricity.

Congressman Phil D. Swing from the state of California and Senator Hiram W. Johnson from the state of California drafted the ‘Swing-Johnson bill’ to execute this report. After several failed attempts, Congress finally passed the “Swing-Johnson bill” for the investigation of the economic and engineering aspects of the future storage reservoir at Boulder Canyon on May 28, 1928. After the investigation, a bill for the Boulder Canyon Project was passed in Congress and the Boulder Canyon Project Act became effective on June 25, 1929. The Boulder Canyon project, which was a multi-purpose water storage, flood control, and irrigation project, was facilitated by the 1922 Colorado River Compact that divided up the waters of the Colorado River among the seven river basin states. Arizona, which had not yet ratified the Colorado River Compact, protested that too much of the river’s water was allocated to California. This dispute would not be settled for several more decades. One of the five purposes of the Boulder Canyon Project was the generation of electricity (Kleinsorge, 1941, p.75-80).

5.4.1.2 Federal imaginaries: the “Public” Hoover Dam

The federal government’s active intent to involve itself in the power market and the high potential of energy generation in the Colorado River Basin was a catalyst for a debate between the public and private power sectors. This debate is related to the question of whether the opportunity of making a profit should be reserved for the private power sector or not. The original 1922 report by Arthur Powell Davis recommended that the sale of hydroelectricity could easily reimburse government construction and operation costs, so the project could be built without any investment from the private sector (Hundley, 1975, pp.113-114).

After the Civil War, which lasted from 1861-1865, there was a debate in America about the nature and purpose of the national government. Some people preferred maximum liberty for economic profits and urged the government to promote industrial capitalism. Even though this political philosophy brought wealth and power to the United States, there remained many social problems from market system failures such as environmental pollution, labor exploitation, boom and bust economic cycles, and natural resources depletion. By the turn of the 20th century a reform movement called "progressivism" advocated a more activist role for government in advancing the public interest. Progressives felt capitalism should be regulated to make it more stable and socially responsible. As for electricity, the Progressives believed that the *laissez-faire* policy was not appropriate for the public welfare, preferring instead the utilitarian principle of "the greatest good to the greatest number." Progressives believed that privately-owned electric utilities providing essential public services should be regulated by the state or the federal government commissions. It was reasonable that the private utility companies and the conservatives were opposed to this regulatory policy. Regarding the ownership of electricity utilities, there were overall four perspectives, that "(1) opposed any government intervention, (2) favored government regulation of privately owned utilities, (3) favored a wholly publicly owned electricity supply system, (4) preferred a hybrid system of private and public utilities." Richard T. Ely, who was known as Progressive economist, insisted the fourth model perceived best for "responsible economic and social development" (Hirt, 2012, pp. 105-108).

The Hoover Dam provided a good opportunity for the debaters who wanted to talk about the private and public initiative in supplying electricity. The private industry was afraid of being compared with the quality and the price of public electricity supply. The specific concern related to governmental involvement was the market price of electricity. According to an article in the *New York Times* in 1933, opponents of public power argued that publicly-financed projects "…can take away existing markets for power from the companies because there are no immediate penalties incurred in selling electricity below cost. Rates can be introduced which would bankrupt private companies but which can be made up by taxation in the case of municipal, State or government projects. Eventually, however, the loss in revenues from taxes now is paid by utility companies, and the costs of operating at a loss, cannot fail to affect the welfare of consumers…" ("Utilities fight public ownership" 1933. Oct. 29th. *New York Times*).

Private power advocates charged that public power was inefficient but that was generally not true at least in 1920s (Hirt, 2012, pp. 205-213). The case of the Hoover Dam refuted this private power advocates' assertion. The Hoover Dam, like all multiple-purpose projects, could supply hydroelectricity at lower cost than the private industry and amortize the construction cost over a longer period at lower interest rates (Kleinsorge, 1941, p.299). Though hydroelectricity already contributed 71% of the energy generated by Los Angeles in 1934 (Kleinsorge, 1941, p.292), after about 10 years, in 1945, approximately 75% of the electricity consumed by the city of Los Angeles came from the Hoover Dam (Copp & Zanella, 1993, p.71) (**Fig. 18**).

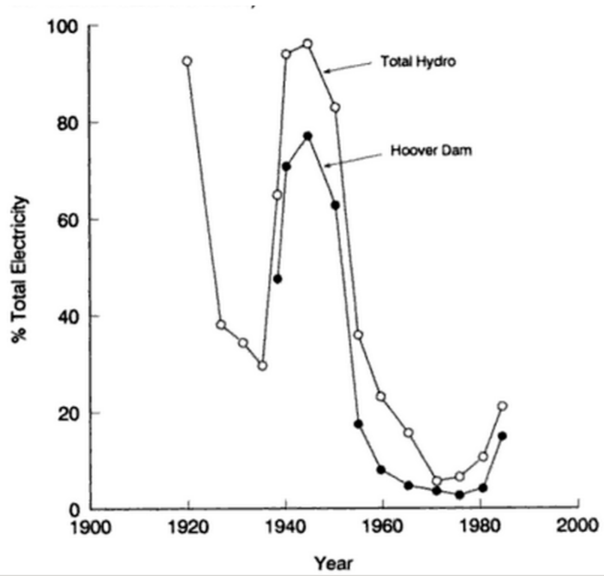

Figure 18. Percentage of total electricity for the city of Los Angeles provided by hydropower from all sources and from Hoover Dam (source: Copp & Zanella, 1993, p.71)

5.4.2 Social and economic backgrounds: hydroelectricity and Hoover Dam

5.4.2.1 Economic backgrounds: hydroelectricity market before Hoover Dam

Before Hoover Dam was built, the electricity market was extensively controlled by the private power utilities as a result of the technological development related to electrical engineering in private power industries. From the 1910s to the 1920s, there was a rapid advance in technology and equipment of transmission system and substation automation system, the utilization of electricity spread widely. Especially in the industry department, with this technological development, the portion of electricity from private sector increased fast. The private power utilities became more interested in a lucrative business model in the power market and according to the economy of scale, the small utilities began to merge into larger consolidated regional utilities. In 1912, the percentage of electricity from private power plants in the whole power market was 28%, and in the 1920s it was over 50%. Only 18 private power companies held half of the hydroelectricity in the United States in 1916. This prevalence of private power utilities had been apparent for about 15 years from 1920. In 1932 three great utility holding companies took control over half of the electricity market in the U.S. However, there was a slightly different situation in the West. As of 1916, 56% of hydroelectricity in the West was tightly coupled with the publicly owned lands. In 1920, the legal background for prompting the publicly owned power utility was established. Protecting Federal participation in the power market and regulating the private utilities, Federal Water Power Act of 1920 boosted the public power market (Linenberger, 2002, pp. 38-40).

5.4.2.2 Social and legal backgrounds: hydroelectricity from Hoover Dam

The construction of Hoover Dam was completed in 1935 and the generators started power in 1936. The generation of electricity, one of Hoover Dam's multiple purposes, was a way to finance the project. The directly benefited area with the protection from flood and irrigation system is limited and this area could not entirely bear the cost of the project. The government also did not have an intention to donate the federal income to this area. Thus, the sale of electricity was considered as the best solution to this conundrum. Moreover, generation of electricity played a significant role to initiate this huge project (Klenisorge, 1941, p.84) which was even labeled as the largest public project in the world at that time. The Los Angeles Bureau of Power and Light constructed the Boulder-LA transmission lines and the lines comprised two rows of towers. The height of each tower was 109 feet and the distance between the two rows was 800 – 1,000 feet. Current Hoover Dam's power annual generation is about 4.2billion kWh (Water and Power Associates, 2014).

The Boulder Canyon Project Act gave the Secretary of the Interior the authority to execute the sale of hydroelectricity. According to the Act, transmission lines should be built by the applicants for making a contract. Because there were no large cities anywhere near Hoover Dam, long transmission lines were needed to get the hydroelectricity from Hoover Dam to markets, so the possible applicants could not make a contract with the Secretary of the Interior to buy Hoover power if they could not have built the transmission lines with their own money. However, the Act had an article to protect small contractors simultaneously, which empowered the Secretary of the Interior to ask a big contractor to share the transmission line with small contractors. This could prevent the duplicate investment for the transmission line and give an opportunity for smaller electric utilities to contract for Hover Dam hydropower (Kleinsorge, 1941, pp.97-98). Hoover Dam marked a transition in how the public and Congress thought about reclamation. Before the Boulder Canyon Project, the Bureau of Reclamation tried to recover project costs from the sale of publicly owned land and the sale of water from the reclamation projects to irrigators. However, land and water sales usually did not generate enough revenue to pay for project costs. To make matters worse, most irrigation districts were behind on their repayment obligations. Hydroelectricity became the answer to change those unpleasant situations. Revenues from electricity sales at large federal dams allowed the government to quickly recoup project expenses and then use surplus revenues to subsidize the irrigation project costs. Hoover Dam was the proof of concept for this new approach to financing reclamation. With the success of the Hoover Dam, the Bureau of Reclamation could promote federal public hydropower projects with confidence (Linenberger, 2002, p.46).

5.5 The Initial Allocation of Hydroelectricity at the Federal Level

5.5.1 Tentative purchasers and collective-choice arrangement (rule-making)

On September 10th, 1929, the Department of the Interior informed all prospective applicants for the Hoover Dam hydroelectricity.[3] The tentative purchasers included the municipal-owned utilities and the states of Arizona, Nevada, and California (The United States Department of Interior, 1933, p.511). Due to the historically cheap price of hydroelectricity from Hoover Dam, the sum of the hydroelectricity purchase contracts requested by applicants exceeded three times the total generation capacity of Hoover Dam (Kleinsorge, 1941, p.287)[4].

Although the states of Arizona, Nevada, and California applied for the hydroelectricity from Hoover Dam, the reasons for applications were completely different. The state of California most strongly wanted to be a buyer of the hydroelectricity. Especially Los Angeles, which vigorously supported to add the hydroelectricity from Hoover Dam to the southern California power market. According to the application, the amount for which Los Angeles applied was 3.6 billion kWh per year, almost the whole hydroelectric capacity of Hoover Dam. The annual capacity to be contracted was 4,240,000,000 kWh (The United States Department of the Interior, 1948, p.69). The lucid explanation came with the social and economical background of Los Angles. First, the consumption of electricity by Los Angeles had increased by 15% annually between 1915 and 1922. In 1930, the consumption of electricity became seven times more than that in 1915 (Pisani, 2002, p.229). Second, Los Angeles was economically boosted by the growth of Hollywood and the oil drilling on Rincon and Signal Hills in the 1920s. It became the largest city in the state of California that decade (Wiley & Gottlieb, 1985, p.108-109). In 1920, the population of Los Angeles was around 0.6 million and the population increased to 1.5 million in 1940 (**Fig. 19**). The rapid growth of population was one of the greatest challenges to supply of energy which was needed not only for electricity provision but also water supply. The needs from the economic and social aspects of the state of California positively required a contract for electricity.

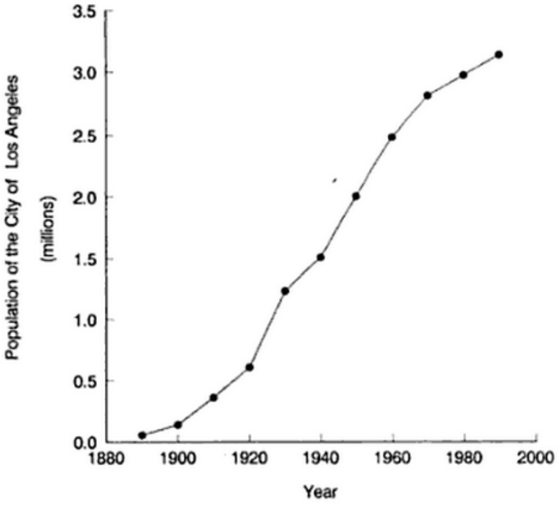

Figure 19. Population growth in the city of Los Angeles

(source: Copp & Zanella, 1993, p.37)

The states of Arizona and Nevada were not able to pay the lease or construction of transmission line. Based on Boulder Canyon Project Act of 1928, they had to build their own transmission line or lease it. However, they had not enough funds for hydroelectricity and transmission. They ostensibly had the 'willingness to pay' for the hydroelectricity, however the truth was that they wanted to buy the hydroelectricity at a low price and sell it to other areas at a higher price than they paid for it (Kleinsorge, 1941, p.288).

In spite of these conflicting backgrounds for applications, the Secretary of the Interior, Ray Lyman Wilbur, favored the policy to provide the states of Arizona and Nevada some of Hoover Dam's inexpensive power. If the ability to afford the payment of hydroelectricity was only criteria, the states of Arizona and Nevada had no choice but to be excluded from the process of the allocation. However, Secretary Wilbur's idea for rule-making was different. This was because Wilbur focused on two criteria for the allocation of power. First, he wanted as many applicants as possible to participate in bidding for hydroelectricity. Second, he attempted to make the benefits from Hoover Dam spread over not only the areas near Hoover Dam but also as more areas as possible (Pisani, 2002, p.231). With this policy, the states of Arizona and Nevada had the opportunity to apply for the allocation of hydroelectricity. The rule for allocation can be seen as an appropriate collective-choice arrangement in that the stakeholders had an equal opportunity to participate in the allocation discussions. In other words, the expectations for the future from the states of Arizona and Nevada contributed to a controversy (*Los Angeles Times*, June 18, 1933, p.26; *Los Angeles Times*, April 10, 1938, p.9; *Los Angeles Times*, October 20, 1929, p.3). The state of Nevada required a third of total hydroelectricity (*The New York Times*, February 16, 1930), and the state of Arizona was not satisfied with the result of allocation. The state of Arizona asserted they deserved to have the right to directly tax the water and hydroelectricity rather than just to take revenue from sale of water and hydroelectricity according to their share portion 18% (Kleinsorge, 1941, p.154). This controversy was kept until the final ratification of the Colorado River Compact by the state of Arizona in 1944.

5.5.2 The condition for the fulfillment of willingness to pay: historically low price

At first, President Hoover did not regard hydroelectricity as a revenue source. He saw hydroelectricity as a sort of spin-off from the need to prevent the Imperial Valley from flooding and provide water supply to Southern California, Arizona, and irrigation farmers. Thus, the rate and the allocation of hydroelectricity were not the main issues for him. However, the intentions of Congress were different from President Hoover. Congress wanted the ownership of generating facilities, the hydroelectricity price, and the right of purchase decision before the completion of construction of the dam. This was because Congress wanted the federal government to have a dominant position in the electricity market. Even though the states of Arizona and Nevada at that time had less actual electricity demand than the amount of power they requested from the federal government from Hoover Dam, they continued to push for a generous allocation of power because of the value of that inexpensive hydroelectricity generated at Hoover Dam.

Before the Hoover Dam, there was private power advocates' assertion that the price of hydroelectricity could not be cheaper than conventional energy sources that prevailed for several reasons (Pisani, 2002, pp.228-229). They also opposed the construction of Hoover Dam for several reasons. First, the construction cost of the hydroelectricity power plant was two to four times more expensive than that of steam power plants with petroleum. Second, with the huge amount of construction cost and the long time required for construction, the price of hydroelectricity would also fluctuate with the change of monetary interest. Third, the generation of hydroelectricity was contingent on precipitation and water intake. Fourth, relatively long transmission of hydroelectricity from the remote dam to the consumers was an obstacle to make the price of the hydroelectricity lower (Pisani, 2002, p.231). Fifth, in the Southwest, there was no sufficient consumption market for the hydroelectricity from the Hoover Dam. For the 4.3 billion kWh of power generation from the Hoover Dam, the market should be enlarged by two times. Lastly, the cost of generation of electricity from steam power plant would keep going down incrementally in the Southwest area (Kleinsorge, 1941, p.285-286). This opposition from private power sector had an impact on the government's decision for the price of hydroelectricity. The construction of Hoover Dam proved the private power advocates' logic wrong. The wholesale price of hydroelectricity from the Hoover Dam was decided at 0.163cents/kWh[5] (Los Angeles Times, December 23, 1931; The United States Department of the Interior, 1933, p.109). It was less than half that of steam power plant electricity. In 1930, the City of Los Angeles and the Metropolitan Water District bought electricity from the oil-fired plant at the price of around 0.4cents/kWh (Copp & Zanella, 1993, p.63). There should be no consumer who could refuse to make a contract with a reasonable price like that. That total amount of all applicants was over three times the total generation of Hoover Dam (Kleinsorge, 1941, p.287). The condition of willingness was unquestionably fulfilled with the historically cheap price of the hydroelectricity from Hoover Dam.

After construction of Hoover Dam, the portion of hydroelectricity in total electricity generated in the city of Los Angeles get to around 95% in 1940 (Fig. 4). It revealed that the private power advocates' concern about consumption market was unnecessary.

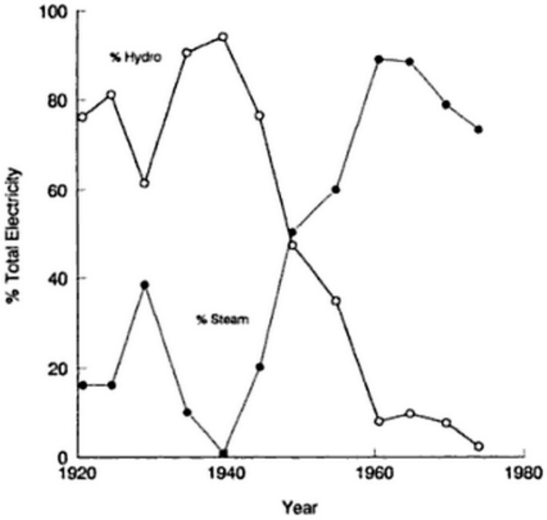

Figure 20. Electrical energy from hydroelectricity and steam power in Los Angeles (source: Copp and Zanella, 1993, p.130)

5.5.3 Agents' negotiation and dispute resolution for making an agreement: from the allocations of water to that of hydroelectricity

5.5.3.1 The Colorado River Compact

The initial allocation share of hydroelectricity for the state of Arizona was connected with the allocation of water for the state through the Colorado River Compact in 1922. In the 1910s, the consumption of the Colorado River by the state of California was increasing rapidly and this made the states near the Colorado River Basin concerned that California might intend to have too much control over Colorado River water. Western water law allocates superior rights to those who make beneficial use of water first: "first in time, first in right." As a result, the League of the Southwest for negotiation of the allocation of the Colorado River was organized in 1919. Simultaneously, the investigation on the feasibility of developing the Colorado River Basin funded by the

Kinkaid act was initiated by Congress in 1920. In 1922, there was a historic agreement among seven states, the states of California, Arizona, Nevada, New Mexico, Wyoming, Utah, and Colorado, at Bishop's Lodge, near Santa Fe in New Mexico (The U.S. Department of Interior, 1933, p.5).[6] With the U.S. Geological Survey's investigation, the average flow of 17.5 million annual acre-feet was divided into two parts, the Upper Basin and the Lower Basin that were divided by the geographical point, Lees Ferry (The U.S. Bureau of Reclamation, 1980, p.4).[7] Each basin was allocated 7.5 million acre-feet. However, the Upper Basin States could not make an agreement about the specific share of allocation in 1922. On October 11, 1948, the Upper Basin States finally confirmed the allocation of water subject to the Colorado River Compact of 1922 with the Upper Colorado River Compact of 1948. According to this agreement, the 7.5 million acre-feet of water should be allocated to the Upper Basin states based on this scheme: Wyoming (14%), Colorado (51.75%), Utah (23.00%), New Mexico (11.25%), and Arizona (0.7%) (The U.S. Bureau of Reclamation, 1980, p.11). On the contrary, the Lower Basin States of California, Arizona, and Nevada made an agreement on the allocation of water in 1922. The allocation for the Lower Basin stipulated in the Notes of the Colorado River Compact of 1922 was like this: 58.7% for the state of California, 37.3% for the stated of Arizona, and 4% for the state of Nevada.

5.5.3.2 The electricity share for the state of Arizona: 18%

The state of Arizona's share of hydroelectricity from Hoover Dam is almost the same as its share of the 15 million acre-feet of water divided among the basin states in 1922. This result was an outcome of the state of Arizona's struggle and litigation for water with its other competitive neighbor, the state of California. The history of this dispute about water and hydroelectricity from Hoover Dam between neighbor states is explored as follows.

A huge public project is likely to trigger a debate between its proponents and opponents and the Boulder Canyon Project, the construction of Hoover Dam, was no exception. The state of Arizona's opposition for the construction was strong. In spite of the agreement on the Colorado River Compact, the state of Arizona changed its mind and hesitated to ratify the compact. The major reasons that the state of Arizona was opposed to this unprecedented project were due to the engineering and economic problems. First, the state of Arizona maintained that the Hoover Dam project was not safe from the engineering point of view. Second, Hoover Dam was unnecessary because there was no need to prevent flood or supply water to the agricultural irrigation system (Kleinsorge, 1941, p.105). In spite of these absurd grounds that the state of Arizona backed, there was a crucial and political reason behind it which was disclosed in the lawsuit case, *State of Arizona v. State of California*. The state of Arizona wanted to own Hoover Dam or at least take compensation for providing lands for Hoover Dam. It was interested in the revenue from the sale of water or hydroelectricity. In spite of political negotiation and appeals, the state of Arizona finally filed a lawsuit in the Supreme Court against the states of California, Nevada, New Mexico, Utah, Colorado, and Wyoming, and the Secretary of the Interior, Ray Lyman Wilbur in 1930. In this lawsuit, the state of Arizona maintained that the Colorado River Compact and the Boulder Canyon Project Act were unconstitutional on the grounds that (a) the act invaded the sovereign jurisdiction over the territory of the state of Arizona (b) it deprived Arizona of the right of water usage in her jurisdictional territory and give the Secretary of Interior a authority to sell the stored water; (c) it did not give the same privilege for the Colorado River to the state of Arizona as that of the state of California; and (d) the Secretary of the Interior should not have the power to sell water and generated hydroelectricity from Lake Mead and Hoover Dam dynamos because the water and power comes from the territory of the state of Arizona, and the Secretary did not offer proper compensation to the state (Kleinsorge, 1941, pp.132-133).

Regarding the fourth question that the state of Arizona raised, the Supreme Court denied the state of Arizona's argument as follows. The government of the United States could do public works without complying with the state of Arizona's law on the United States territory for the fact that the authorization from Congress for the construction of the Hoover Dam would legally suffice (Kleinsorge, 1941, pp.132-133). The federal government had owned most area of the Colorado River Basin except the private lands since the United States acquired that territory from Mexico under the Treaty of Guadalupe Hidalgo on February 2, 1848. Moreover, based on the Constitution of the United States, Congress has the authority to make and eliminate regulations in relation to the territory of the United States (Kleinsorge, 1941, p.128). The Supreme Court also contended that the public works based on the Boulder Canyon Project Act would be perpetually owned by the United States and under tax exemption from the state of Arizona's taxation (Kleinsorge, 1941, pp.132-133). Thus, there was no financial loss to the state of Arizona and the United States had no obligation to give appropriate compensation to the state of Arizona for selling water and hydroelectricity. Seeing that its legal challenges were not going to succeed, in 1944 the state of Arizona finally ratified the Colorado River Compact. The initial allocation of hydroelectricity for the state of Arizona was 18% and this portion is approximately equal to the state's share of the whole water from the Colorado River. The amount of water allocated to the seven basin states from the annual flow of the Colorado River was 15 million acre-feet, and the share of the state of Arizona was 2.8 million acre-feet, around 18% in 1922—according to Section 8(b) of the Boulder Canyon Project Act, the benefits from the Colorado River and Hoover Dam should be divided based on the Colorado River Compact.

5.5.3.3 The interim allocation of hydroelectricity (Oct. 21st, 1929)

Regarding the first allocation of electricity, the state of California contractors took 100% of hydropower at first. On October 21st, 1929, the Secretary of the Interior decided the allocation of Hoover Dam hydroelectricity. Before the final close, there was a formal hearing process prepared by the Secretary of the Interior on November 12th. The decision was as follows. The Metropolitan Water District of Southern California acquired 50% of hydroelectricity of Hoover Dam, 25% of hydroelectricity was allocated to the City of Los Angeles, and 25% to the Southern California Edison and associated companies (The U.S. Department of the Interior, 1933, p.517). Put simply, 100% of hydroelectricity was allocated to the state of California (The U.S. Department of the Interior, 1933, p.526).[8]

This allocation was tentative and for the states of Arizona and Nevada, 36% was reserved with privilege for 50 years. So, the state of California has to be subject to the request of the states of Arizona and Nevada if these states require their share, 36% at any time. Later, Arizona and Nevada demanded their purchase of the 36% of Hoover's electricity allocated to Arizona and Nevada. The contractors of the state of California relinquished the allotment of 36% proportionally. In 1941, 18% of the total hydroelectricity was allocated to the Nevada and the remaining 18% to Arizona in 1945. In 1945, the Arizona Power Authority, a public entity of the state of Arizona, made a contract with the Bureau of Reclamation for the purchase of Arizona's portion of the Hoover Dam's hydroelectricity. The first delivery was accomplished in 1951 (Arizona Power Authority, n.d.).

5.5.3.4 The confirmation of initial allocation

According to the Boulder Canyon Project Act, the Secretary confirmed the initial allocation of hydropower by May 1941. The allocation percentage is as follows.

Table 4. The initial allocation of hydroelectricity from Hoover Dam (source: The Bureau of Reclamation, 1980, p.57)

Contract no.	Contractor	Firm energy Allocation %	Date of Execution	Date of Termination
I1r-1334	Dept. of Water & Power	17.5554	May 29, 1941	May 31, 1987
I1r-1336	Metropolitan Water Dist.	35.2517	May 29, 1941	May 31, 1987
I1r-1455	State of Arizona	17.6259	May 29, 1941	May 31, 1987
I1r-1338	State of Nevada	17.6259	May 29, 1941	May 31, 1987

I1r-1335	So. Calif. Edison Co.	7.0503	May 29, 1941	May 31, 1987
I1r-1340	City of Glendale	1.8475	May 29, 1941	May 31, 1987
I1r-1337	City of Pasadena	1.5847	May 29, 1941	May 31, 1987
I1r-1341	Calif. Electric Power Co.	.8813	May 29, 1941	
I1r-1339	City of Burbank	.5773	May 29, 1941	

The revenue from selling the electricity has been used for amortization of the investment cost of Boulder Canyon Project for 50 years. The total cost for the project was $145,181,882 as of 1969. The revenue has been also put into the Colorado River Dam Fund for annual operation and maintenance of the Colorado River and its tributaries by Congress. The dam and power plant facilities are owned by the federal government of the United States and the federal government is responsible for the operation and maintenance of the dam and facilities as well. The Federal Government owns the facilities for generating, transforming, and switching hydroelectricity at the dam itself, but does not own or maintain the high-voltage transmission lines taking power from the dam to utilities and customers in the three states. The operation and maintenance of the transmission facilities serving California were delegated to the Department of Water and Power of the City of Los Angeles and the Southern California Edison Company, Ltd. This delegation contract had been effective from 1937 to 1987 The Bureau of Reclamation, 1980, p. 11).

In 1977, the Bureau of Reclamation started preparing the re-allocation of hydroelectricity from Hoover Dam since the 50-year contracts were due to expire in 1987. On Oct. 1st, 1977, the administrative jurisdiction for the transmission of hydroelectricity and contracts for the purchase of federal hydroelectricity were taken over by the Western Area Power Administration (WAPA) from the Bureau of Reclamation, through the Bureau of Reclamation is still in charge of operation and maintenance of the dam and its power plant**.**

5.6 Institutional Adaptations in the Allocation of Hydroelectricity

5.6.1 The second phase of the allocation of hydroelectricity: The Hoover Power Plant Act of 1984

In preparing for the termination of the criteria established by the Boulder Canyon Project Act in 1987, the Hoover Power Plant Act of 1984 regulated the allocation of hydroelectricity of the Hoover Dam. The Hoover Power Plant Act allocated hydroelectricity of the Hoover Dam to the contractors such as states, municipalities, and utilities according to three schedules (Schedule A, B, C). The Act entailed the Hoover Uprating Program and set the amount to fulfill the Lower Colorado River Basin Development Fund. This fund was to support the Central Arizona Project (CAP) financially. The Hoover Power Plant Act of 1984 imposed .0045 cents/kWh on purchases of hydroelectricity to fund CAP.[9] Though this subsidy was a few cents per person per day, 2 million users could generate several million dollars per year. In addition, the U.S. Department of the Interior entitled CAP to have the right to buy the hydroelectricity of Hoover Dam at a cheap price and resell that at the higher market price (Reisner, 1993, p.304). The Hoover Power Plant Act of 1984 is effective from 1987 to 2017.

The Hoover Uprating Program updated generation units at Hoover Dam and finished it in 1993. Ten 82,500kw power units were changed into 130,000kw units. Two 82,000kw power units were upgraded to 127,000kw units. The remaining 82,500kw power units were replaced to 130,000kw and the 40,000-kW unit replaced to 61,500-kW and the 50,000-kW unit replaced to 68,500-kW (The Bureau of Reclamation, 1995, p.49).

The Hoover Power Plant Act of 1984 updated the initial allocation of hydropower entitlements reflecting the change of situations of Hoover Dam hydroelectricity. Schedule A refers to the initial allocation frame for the contractors of Hoover hydroelectricity according to the Boulder Canyon Project Act of 1928. The contractors are Metropolitan Water District of Southern California, the city of Los Angeles, the city of Glendale, the city of Pasadena, the city of Burbank, Southern California Edison Company, Arizona Power Authority, Colorado River Commission of Nevada, and the city of Boulder City. Second, the Act also determined that the increased long-term generation capacity of Hoover Dam achieved by the Uprating Program would be distributed according to Schedule B which allocates the additional power to both traditional and new customers that helped fund the Hoover Uprating Program. According to the Hoover Power Plant Act of 1984, the States of California, Arizona, and Nevada could get more hydroelectricity. Complying with the Hoover Power plant act of 1984, the hydroelectricity allocation portions for each state are 23.4% for Nevada, 19% for Arizona, and 57.6 % California ("Hoover Power Allocation Act, Senate Report 112-58).[10] Schedule C guides the allocation of any "excess" hydroelectricity. The allocation depends on the negotiation between the states of Arizona, Nevada, and California and the federal government (Western Area Power Administration, DOE, n.d.).[11]

5.6.2 The third phase of the allocation of hydroelectricity: The Hoover Power Allocation Act of 2011

In 2011, the US Congress passed a new bill amending the 1984 act, the Hoover Power Allocation Act of 2011 (HPAA) in anticipation of the 2017 expiration of the Hoover Power Plant Act of 1984. President Obama signed this bill into law on Dec. 20th, 2011. This bill has a new allocation criterion, called Schedule D. This criterion is designed to create opportunities for adding new customers to get access to inexpensive Hoover power. According to Schedule D, traditional Schedule A and B contractors must deduct 5% of their allocation of hydroelectricity for new contractors. This deducted hydroelectricity will be allocated to federally recognized Indian Tribes and other eligible contractors that currently are not included in the purchaser group.

Schedule D allocation of power of “re-distribution” of the common pool resource can be justified for a couple of reasons regarding the benefits from common pool infrastructures associated with Hoover Dam. First, Schedule D allocation of deducting some power (5%) from the Schedule A and Schedule B contractors and allocating this to other “new” contractors can be best understood in historical context. Regarding the Colorado River Compact, the divergent Indian Tribes were not asked to participate in the discussions of the allocation of the Colorado River. Though they had depended on the Colorado River basin longer than the farmers and the residents, they were not included among the allottees of water and hydroelectricity from Lake Mead and Hoover Dam (Worster, 1985, p.211). The Schedule D re-distribution of hydropower allocations partly addressed this injustice toward Indian Tribes. Second, this "re-distribution" definitely fits into Secretary Wilbur's initial idea for allocation of hydroelectricity, enhancing the opportunity for participation and spreading widely the benefit of the electricity commons. Therefore, the deduction of some people's vested interests to benefit those who had previously been excluded from this CPR can be understood as a successful adaptation of the institutional arrangements governing this sociotechnical infrastructure.

The Western Area Power Administration (WAPA) allocated one-third of Schedule D power to the Arizona Power Authority for the state of Arizona, the Colorado River Commission of Nevada for the state of Nevada, and WAPA for the state of California. The remaining two-thirds (approximately 66.7%) of the Schedule D power was allocated to WAPA for the federally recognized Indian tribes, the Arizona Power Authority for the state of Arizona, and the Colorado River Commission of Nevada for the state of Nevada (Lisa Lien-Mager, n.d.).[12] However, the act does not explain the specific procedure for allocating of hydroelectricity of Schedule D within the states (Arizona Power Authority, n.d.).[13]

A dispute on priorities among the users for the allocation of power has been provoked by the Schedule D allocation. The states of Arizona and Nevada did not agree with the allocation of Schedule D in 2011. According to Schedule D scheme, approximately 66.7% of hydroelectricity of Schedule D should be first allocated to federally recognized Indian tribes and then to new allottees in Arizona and Nevada. The states of Arizona and Nevada asserted that they could not accept the higher priority of Indian tribes over the current allottees. They maintained that there was no legal evidence for establishing different allocation priorities. In addition, the states of Arizona and Nevada contended that because Hoover Dam is situated on the border of Arizona and Nevada, they deserve higher priority access to Hoover hydroelectricity and the revenue from selling the hydropower. From the initial legislative establishment of power allocations, a relatively larger portion was allocated to the state of California because the state of California was expected to need more power due to the projected rapid growth of industry and population. In allocation criteria, Congress and the Department of the Interior gave weight to the fact that the Boulder Canyon Project (Hoover Dam) was provoked from the necessity of water and electricity supply in California's irrigation system and prevention of Colorado River floods (Arizona Power Authority, n.d.).[14] In spite of the objections of the states of Arizona and Nevada, the Indian tribes were provided first priority for the Schedule D power conclusively (WAPA, n.d.).[15]

Recently, the Western Area Power Administration (WAPA) has finished the process of receiving the applications for Schedule D allocation. WAPA received 107 applications by March 31, 2014 and allocated the Schedule D hydroelectricity, 80,680 kW to appropriate applicants considering their priorities and general eligibility. WAPA closed the comments period for this allocation on September 19th, 2014. In the allocation process, the Native American tribes were taken in first consideration and then the remaining hydroelectricity was distributed to the eligible applicants (WAPA, n.d.)[16].

5.7 Conclusion

This chapter investigated the federal level arrangements for the construction of Hoover Dam and the allocation of its resources (water and electricity). Hoover Dam is a sociotechnical infrastructure. Constitutional level institutions, such as the 1929 Boulder Canyon Project Act and the 1922 Colorado River Compact, have supported the transformational change in the water and electricity systems in 1930s. Regarding the hydroelectricity and water resources from Hoover Dam as a common pool resource, layered social and institutional arrangements at the federal level have supported and set up imaginaries, epistemologies, and rules for the sustainable allocation of resources.

Institutional arrangements, which have been the condition *sine quo non* in development of water and energy systems, have worked properly for the maximized utility of Hoover Dam based on agreements among lower basin states. With institutional management, the sociotechnical systems of Hoover Dam have been sustainable, and seven basin states and other industries have benefited from the sociotechnical resources, water and electricity from Hoover Dam for 80 years. Without institutional management, resources inevitably become depleted or overused by a limited number of users with privilege. Also, the updated rules on the allocation of electricity in response to social, economic, and political changes reflect the flexible management of institutions.

In particular, on the basis of the eight conditions that Ostrom suggested for sustainable management of common pool resources, in the case of Hoover Dam the collective-choice arrangement for determining hydropower allocations appear to provide somewhat equitable opportunities to the stakeholders (the states of Arizona, Nevada, and California, and later the regional tribes) to influence allocations and subsequent re-allocations. The Colorado River Compact and the effectiveness of the Boulder Canyon Project Act, first, provided the foundation for the allocation of water resources and hydropower entitlements. Moreover, the evolving hydropower allocation process shows that the institutional arrangements exemplify “resilience” because the allocations of water and hydropower were both stable in the short-term and adaptable in the longer term (adapted in 1984, 2007, and 2011) which entail long-lasting debates as well as political/legal dispute resolution processes.

The next chapter illustrates how current institutions have supported the operation, regulation, and transformation of water and energy systems within the state of Arizona. Also, the resilience work of different types of institutions will be articulated.

CHAPTER 6

WATER AND ENERGY SYSTEMS IN ARIZONA: THE ROLE OF INSTITUTIONS IN SOCIOTECHNICAL SYSTEMS RESILIENCE

6.1 Introduction

Chapter 6 builds on the work of Chapters 3 and 4, which argued for the need to thoroughly understand the institutional work of resilience and the institutional landscapes of critical infrastructure systems. Resilience is a capacity to sustain, adapt, and transform systems responding to disturbances to systems. Chapters 3 and 4 discussed the characteristics of institutions—stable yet flexible— and proposed a redefinition of resilience around this idea. Moreover, Chapters 3 and 4 revealed the importance of resilience work for sociotechnical systems: sustaining, adapting, and transforming then over time to create stability and flexibility. The degree to which institutions can sustain, adapt, and transform infrastructures determines the dynamic resilience of infrastructures.

Chapter 6 applies the frameworks of institutional analysis and resilience defined in Chapters 3 and 4 to the resilience work of institutions that govern water and electricity supply in Arizona. Chapter 6 first describes Arizona's three primary water resources: the Colorado River, the Salt River, and underground aquifers. Each water resource uses respective water infrastructures: Central Arizona Project (CAP) canals, Salt River Project (SRP) dams and reservoirs, and natural aquifers as well as underground water storage facilities. These water infrastructures currently face pressing technical and social challenges: the fluctuations of mountain snowpack and precipitation, long-term droughts, the higher probability of 'a shortage declaration' of Colorado River, population growth, groundwater depletion, and the political pressures of water entitlement negotiations in the Colorado River basin areas. More importantly, the successful management of the complex water systems is tightly linked to the operational practices of and water regulations that govern electricity utilities (e.g., Arizona Public Service, Salt River Project, and Tucson Electric Power) which consume cooling water and supply electricity to municipalities such as the city of Phoenix and Tucson in Arizona.

Chapter 6 investigates three types of infrastructure institutions: i) infrastructure-level practices that control the inflow/outflow of Colorado River water and Salt River water within normal operational ranges; ii) state-level regulations adapt the utility practices of groundwater pumping for the resilience of socio-eco-technical systems in Arizona; and iii) federal-level water rights decisions, the reallocation of Colorado River water, and social forces that impinge on groundwater management. All three play a significant role for the resilience of Arizona and the Southwest.

In brief, the contribution of Chapter 6 is three-fold: i) understanding and mapping the institutional landscape of water and energy systems; ii) unbundling the lateral, vertical, and longitudinal threads of institutions governing this landscape; and iii) finally, describing the dynamic management of resilience work done by operational, regulatory, and constitutional institutions. Understanding this landscape of resilience work done by operational, regulatory, and constitutional institutions is essential to improve the resilience of sociotechnical infrastructures.

6.2 Water-Energy Nexus in Arizona: water availability issues

Water availability issues have been one of the most critical challenges to the management of water and energy infrastructures in the US and Arizona. Recently, several socio-technical phenomena and preceding researches in the U.S. have drawn significant attention to the tightly bound water and energy systems from the perspective of vulnerability and resilience. First, climate change increases the frequency and intensity of extreme heat temperatures and droughts in the Southwest (Garfin et al., 2013). As a consequence, the availability of water supply in all sectors—water and electricity utilities, agricultural irrigation, municipalities, and states—is expected to decrease (Miller et al., 2008). Second, the thermoelectric power plants took 41% of fresh water and this share is more than any other sectors, such as irrigation, drinking water, and the industry in the U.S. (Kenny et al., 2009). At the same time, extensive electricity is used to produce and move water. Third, in 2010, the Browns Ferry nuclear power plant in Athens, Alabama, showed the correlation between the impact of climate change and the curtailment of electricity generation. From July 24th to August 23rd, the three reactors of the Browns Ferry nuclear power plant reduced their power output to 60% due to the hot surface water (NRC, 2010). Arizona has a large nuclear power plant (Palo Verde) that can be similarly affected by rising temperatures.

These water-energy nexus challenges also arise in the context of water and energy systems in the Phoenix Metropolitan Area (PMA). Those systems both consume great energy to move water and use diverse sources of water for electricity generation. Arizona’s energy systems heavily depend on Colorado River water for cooling thermoelectric generators. Currently, 90% of utility-scale net electricity generation comes from thermal generators as of January 2019 in Arizona (EIA website). Water supply is essential for the cooling system in thermoelectric power plants. Wet-cooled combined cycle plants of APS use approximately 295 gallons/ MWh (APS, 2017, p.184). The electricity generation in Arizona that is largely reliant on thermal power plants may see a decrease of as much as 10% due to water shortages during drought cycles (Bartos & Chester, 2015; 2016). The following sections will first describe the landscape of water and energy systems in Arizona within which resilience work occurs and then how resilience work of institutions at different scales—such as recurrent practices, anticipatory regulations, and transformative constitutions—has contributed to the functionality of water and energy systems in Arizona.

Many studies investigated the impact of climate change on the relations between infrastructure and institutions regarding water and energy systems. For instance, the curtailment of some power plants’ generation due to extreme climate events has drawn our attention to resilience and vulnerability of water and energy systems (DOE, 2014). This recent socio-technological phenomenon stresses the findings of the latest research underscoring the institutional coordination in managing water and energy systems coupled infrastructures (Benson, 2009; Conrad, 2010; Gold & Bass, 2010; NETL, 2010;

Scott et al., 2010, 2011; Sovacool, 2009). Yet these studies did not adequately examine the fundamental role of the institutions, which govern highly coupled water and energy systems. Importantly, we need to delve into the contribution of institutions to critical infrastructure from the perspective of resilience. A more astute question should be how critical infrastructure retains their functionality and what role the institutions play to contribute to or subtract the functionality or capacity; that is, the resilience of critical infrastructure to climate change.

6.3 The Development of Water and Energy Systems in Arizona

6.3.1 The initial development of centralized water and energy systems

Before the 1911 completion of Roosevelt Dam as the first large centralized socio-technical water control structure in Arizona, localized and simple water and energy systems dominated. One of the original water supply systems was in Tempe, composed of three twelve-inches-diameter wells and 30 horsepower (HP) generators to pump up groundwater into the Tempe Butte reservoir in downtown Tempe. In December 1902, the first tap water was delivered to the consumers in Tempe using gravity (Tempe Public Works Department, 2012). After the Newlands Reclamation Act was passed by the US Congress under the Theodore Roosevelt administration on June 17th, 1902, the U.S. Reclamation Service was created. The establishment of the U.S. Reclamation Service institutionally facilitated issuing bonds for public irrigation infrastructure projects.

In Arizona, the first publicly funded irrigation project, the Salt River Project, was initiated by the Reclamation Service in cooperation with local landowners who formed the Salt River Valley Water Users Association. For financing, the Salt River Valley Water Users Association (which later became SRP) mortgaged lands owned by project members to fund ten million dollars of the construction cost for Salt River Dam #1 (Roosevelt Dam, constructed from 1906 to 1911). However, a more fundamental issue had to be clarified before the construction. Disputes concerning water rights occasionally occurred among the landowners in the Salt River Valley Water Users Association. They needed rules to govern ownership and allocation of water resources, including the stored water that would become available after the construction of Roosevelt Dam and reservoir. In 1904, the distinction between groundwater and surface water was confirmed by the Arizona Territorial Supreme Court in the *Howard v. Perrin* case. The landowner owned the groundwater, which was not subject to the appropriation right of surface water. In 1910, a well-defined institution to govern water resources in Arizona was affirmed by the judiciary again. Judge Edward Kent confirmed appurtenance rule for groundwater – groundwater was subject to the ownership of overlying land - and prior appropriation rule for surface water in *Hurley vs. Abbott* case. His decision developed into the basis of the Public Water Code of 1919, which became the founding rules for water governance in the Valley later.

The stable supply of hydroelectricity and water from Roosevelt Dam (name changed in 1959) has been rooted in the sociotechnical arrangements of the state of Arizona. Water and hydroelectricity from Roosevelt Dam and the related facilities belonged to the U.S. government. The first people served by the hydroelectricity from Roosevelt Dam comprised only 13 customers. In 1912, the water association made a contract with the Miami Copper Mine, which was a prominent industry, to supply it with hydroelectricity for mine operations. In 1917, the Secretary of Interior and the Salt River Valley Water Users Association signed a supplemental contract to turn over operation and management of the federal dam and irrigation structures and facilities, including power generators and transmission lines to the water association. In 1937, the water users association convinced the Arizona legislature to create a new public entity titled the Salt River Project Agricultural Improvement and Power District to assume the management of the dams and hydropower system, which by then included Roosevelt (1911), Mormon Flat (1925), Horse Mesa (1927), and Stewart Mountain (1930) Dams. This new public utility company soon became commonly known as SRP (ADWR, n.d.; Century One, 1969; SRP, n.d.; SRP, 2003; Salt River Project, 1980).

6.3.2 The current complex landscape of water and energy systems in Phoenix metropolitan area

Since then, the state of Arizona has further extended an artificial and increasingly complex sociotechnical water and energy infrastructure to serve the central valleys of the state where most of the population and agriculture exist. Water and energy systems are complex and tightly coupled in Arizona. With regard to the state's water supply portfolio, the multi-state Colorado river makes up 40.2%, in-state rivers (Salt River, Verde River, Gila River and others) make up 17%, groundwater 39.5%, and reclaimed water 3.3% (ADWR, 2015). Central Arizona Project (CAP) infrastructures deliver Colorado River from Lake Havasu to the three counties, Maricopa, Pinal, and Pima counties in Arizona. CAP delivers Colorado river through the 336-mile long canal system, which was completed in 1992 with approximately 5 billion dollars supported by the Colorado River Basin Project Act of 1968. The canal system elevates Colorado river water up to 2,400 feet using 14 pumping facilities (Hanemann, 2002; USBR, 2008). In addition, the pumping and delivery of the Colorado River by CAP aqueducts and treatment of this water need an enormous amount of electricity. For instance, the main water resource for the city of Tucson in the south of Arizona is the Colorado River water from Lake Havasu. The water conveyance from Lake Havasu to Tucson Metropolitan area consumes 3,140 kWh/AF electricity. This is four times more than that of groundwater pumping in the Tucson area (Hoover, 2009). The total electricity consumption for the 1.6 million AF CAP water delivery is about 2900 GWh annually (CAP, 2011).

As stated above, behind the physical landscape of CAP delivery, there are the complicated and coordinated regulatory rules among stakeholders for governance of common resources such as Colorado River water through Colorado River Compact (1922) and Arizona's ratification (1944), Supreme Court decision (1963) and other formal rules. Looking at the specific water supply portfolio in the city of Phoenix area, the water supply system shows a distinctive landscape which is different from that of Arizona. CAP delivery infrastructures supply 44% of water resources to the city of Phoenix with Colorado River water, and SRP, a water utility 50% of consumptive water to the service area within the city of Phoenix boundary. SRP's water infrastructures are composed of seven reservoirs, 1,300 miles long canal systems and approximately 270 wells. The capacity of 270 pumping wells is about 340,000 AF per year and the total storage of seven reservoirs is 2,328,201 AF. Groundwater takes 3% and reclaimed water

3% for the remains (City of Phoenix, 2011). The electricity needed for the water system in the Phoenix Metropolitan Area comes from two sources: SRP and a large investor-owned utility company, Arizona Public Service (APS). The two utilities divide the greater Phoenix metro electric market into two roughly equal halves. As a for-profit utility, APS is regulated by the Arizona Corporation Commission (ACC). As a non-profit utility, SRP is governed by an elected board of directors.

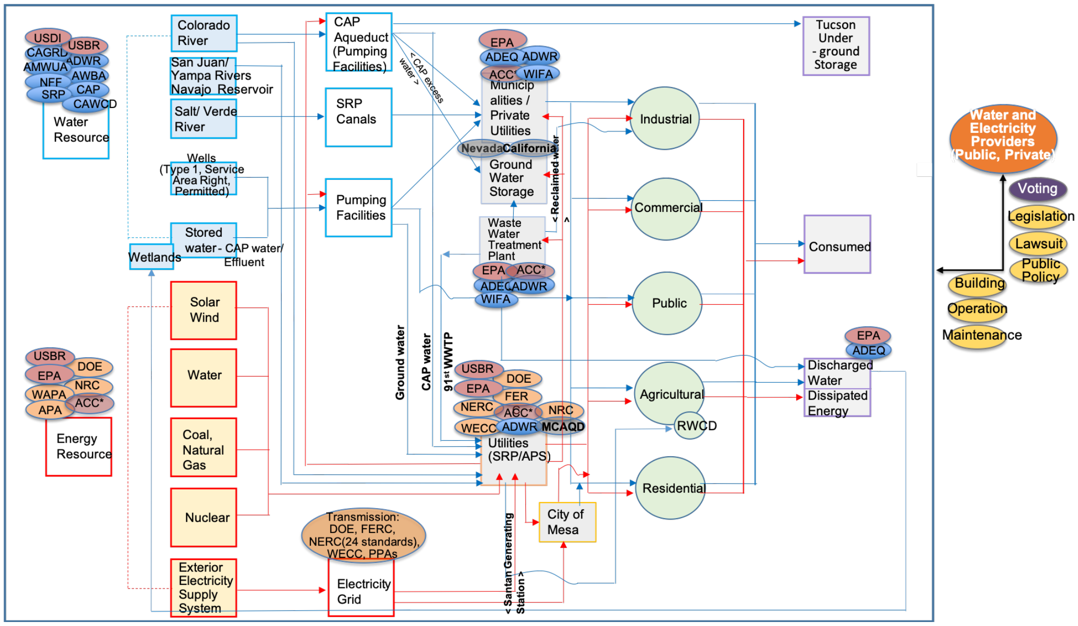

Figure 21. The institutional and infrastructural mapping of water-energy nexus in the PMA (source: Changdeok Gim, author)

* (Abbreviations) United States Interior Department (USID); United States Bureau of Reclamation (USBR); Department of Energy (DOE); Nuclear Regulatory Commission (NRC); Department of Energy (DOE); Environmental Protection Agency (EPA); Central Arizona Groundwater Replenishment District (CAGRD); Arizona Department of Water Resources (ADWR); Arizona Department of Environmental Quality (ADEQ); Water Infrastructure Finance Authority of Arizona (WIFA); National Forest Fund (NFF); Western Area Power Administration (WAPA); Arizona Power Association (APA); Arizona Public Service (APS); Maricopa County Environmental Services Department (MCESD); Roosevelt Water Conservation District (RWCD)

When it comes to electricity system, the purpose of the related regulatory institutions is distinct from water allocation regulatory and constitutional institutions, in that the reliability of electricity supply, not allocation, has been emphasized as a focal point. Myriad issues like electricity outages, rates, and low service quality were caused by fragmented institutions and infrastructures. Responding to these issues, the new organization, Department of Energy instead of Bureau of Reclamation or Department of Interior was established as a responsible organization and a variety of centralized and regulatory sub-organizations for the reliable supply of electricity have emerged. At the federal level, Federal Energy Regulatory Commission (FERC) (the Federal Power Commission established in 1920), NERC (North American Electric Reliability Corporation), WECC (Western Electricity Coordinating Council) regulate the transmission and distribution standards/quality of electricity. At the state level, Arizona Corporation Commission (ACC) has been responsible for the revenue requirement, resource acquisition, securities issuance, affiliated interests, service standards and quality[17] (RAP, 2016). Climate change as a new manufactured risk (Beck, 1992) prompted Environment Protection Agency's (EPA) involvement and effect on the decision of electricity utilities with CO_2 emission regulations issue to add up regulatory complexity such as Clean Power Plan.

An in-depth view into the relationship between water and energy systems in Arizona unveils a more complex narrative. For instance, APS that supplies electricity for much of the water system in Phoenix Metropolitan area uses a diverse spectrum of water resources –effluent (61%), surface water (21%), and groundwater (18%)—for cooling the electricity generators (Arizona Public Service, 2014). Institutions for extraction, contracts, allocation and treatment for these natural and artificial water resources for cooling water used in the ten power generation stations of APS have evolved from a single organization and institution—Bureau of Reclamation and governance of Colorado river's water and power –to more complex network system since the era of reclamation in 1930s. In particular, regarding the allocation of Colorado River water, the institutions have grown into more complex through negotiations and litigations among the stakeholders. For example, entitlements for consumption of Colorado River water in Arizona was acquired by the legal contract with the Bureau of Reclamation. This water consumption includes all diversions such as wells drawing out water from the Colorado River aquifer pursuant to the Boulder Canyon Project Act of 1928, Section 5 and Consolidated Decree by U.S. Supreme Court decision in *Arizona v. California*, 547 U.S. 150 (2006). (Jason Robison et al., 2012; USBR, 2010**).**

Besides, in 1996 an innovative institutional arrangement to augment water availability in Arizona, which contributes to climate resilience of water system in Arizona, was facilitated. Arizona Water Banking Authority (AWBA) for water that is not utilized by Arizona was established. Before AWBA, Arizona cannot use the full 2.8 MAF of allocated CAP water. With intrastate and interstate water banking system, Arizona was able to store the excess Colorado River water as well as water that Nevada does not utilize fully. Currently, the AWBA has accrued about 4 MAF of long-term storage credits (LTSC) which is composed of about 3.4 MAF for Arizona and 0.6 MAF for Nevada according to Lower Basin Water Banking Regulations of 1999. Moreover, in February

2014, under the agreement between the Arizona Municipal Water Users Association (AMWUA) and the Southern Arizona Water Users Association (SAWUA), an Inter-AMA water storage contract between the Phoenix AMA and Tucson was established. On the basis of this legal agreement, a CAP Municipal and Industrial (M&I) subcontractor in the Phoenix AMA is able to store the water, which is not utilized, in the Tucson underground storage facilities. In the case of a 'shortage' declaration, the CAP M&I subcontractors in the Phoenix AMA can consume some of the CAP water that would go to Tucson and in exchange, Tucson would recover that amount of lost water by pumping Phoenix's LTSC water stored within the Tucson AMA. With this fascinating institutional coordination, the Tucson CAP M&I subcontractors can use the stored water instead of depending on the delivery of Colorado River water (AWBA, 2014; Colby & Jacobs, 2007; Megdal, S. et al., 2014; USBR, 2014).

The legal mechanism that determines how much Colorado River is allocated to CAP and a contract structure between CAP and Bureau of Reclamation are also much complicated. First, the water allocation decision for CAP is highly dependent on the Annual Operating Plan for Colorado River Reservoirs. According to the federal level legal framework, the Secretary makes the Annual Operating Plan for Colorado River Reservoirs (AOP). The AOP is a single, integrated document for the water operation and the Bureau of Reclamation's practical institutional governance for Colorado River Reservoirs. In AOP of Colorado River, hydrologic conditions and water releases from the storage system during the last year and projects water operations for the current or next year are explicated. The allocations and releases of the Colorado River reservoirs are varied on the basis of the AOP. If it is confirmed that there will be no ‘shortage’ on Colorado river reservoirs based on AOP, the year-based contract for the excess water can be allocated to CAP (AWBA, 2014; U.S. Department of the Interior, 2007b; 2010a; 2010b). Second, during a ‘shortage’ or extended drought season, the availability of the contingent ‘excess water’ from CAP depends on the allocation priority for Colorado River water. Each user of Colorado River water holds a different priority level from the first (or the highest) to the sixth (or the lowest). For instance, the Central Arizona Water Conservation District (CAWCD) is entitled to 1.49 MAF per year with fourth priorities. In addition, CAP water system also depends on a more specified priority institution for CAP water allocation. Thermoelectric power plants in Arizona which use CAP water with lower priorities for cooling generators should find alternative water resources through institutional coordination such as water right exchanges in case of ‘Shortage’ declaration by the Secretary of Interior (*personal communication, August 17, 2015*). This is because in ‘Shortage’ declaration case, a user who is dependent on lower priority water, for instance ‘excess’ water, cannot be provided with Colordo River water. Third, the institutional framework for Colorado River water in Southwest was extended into a more sophisticated structure with the 2007 Interim Guidelines to cope with drought. This institutional change enhanced resilience capacity of water and energy systems in Southwest to retain functionality responding to an exogenous stressor, drought.

6.3.3. Salt River Project (SRP)

In the map of water and energy systems in Arizona, USBR, ACC, SRP, ADWR, and MCAQD are viewed as common governance nodes making compounding impacts on energy-water linkages. Among these, SRP, a quasi-political entity, is operating and managing both water and energy supply.

SRP is comprised of two organizations. The first is a private water corporation known as the Salt River Valley Water User's Association (the Association) which was founded in 1903 to supply sufficient water for the agricultural stakeholders in the Salt River Valley. The second one is the Salt River Project Agricultural Improvement and Power District (the District) established in 1937 as a public utility and political subdivision of the State of Arizona (Phillips et al., 2009). The Association and the District work as governing institutions for the water and electricity within the boundary of the Salt River Reservoir District.

The Salt River Reservoir District is divided into ten geographical voting districts (or divisions). The Association and the District of the Salt River Project are governed by the elective officials from ten districts (divisions), plus four at-large directors. Landowners elect the ten members of the Association within the Association boundary and each of the ten districts elects one director and three council members. Ten directors, plus a president and vice-president, and thirty council members are the total elective officials for the Association. Fourteen district directors, plus the same president and vice-president, and the same thirty council members are elected by the landowners within the District boundary. The president and the vice president as well as the four at-large directors are elected from all the voting divisions. Electors must be the owner of qualified land within the 1937 reservoir District boundary. An individual who has been appointed by the trustee(s) of the qualified land has also the right of voting. The voting system for the 10 district and association directors is based on an acreage-based system. The owner of 1acre land has 1 vote; 5 acre owner has 5 vote; half acre owner, 0.5 vote. The election of the officials is on the first Tuesday in April of even-numbered years (the Association 2015; the District 2015).

SRP delivers in average 950,000 acre-feet of water from three water resources—seven reservoirs, groundwater, and the Colorado River by CAP (Central Arizona Project) to a 375 square-mile area. The water amount of annual supply by SRP is 736,041 acre feet/year (SRP, 2014). While nearly all of the water service territory was originally farmland, 90% of it is now urban. SRP's seven reservoirs' total storage capacity is 2,300,000 acre-feet. SRP operates around 250 groundwater wells. The annual maximum pumping capacity from theses wells is 325,000 acre-feet. SRP acquires some Colorado River water through the CAP canal, but mostly serves to transport that water to other purchasers. SRP makes an agreement with the CAP and receives the available Colorado River water (Phillips et al., 2009).

SRP provides electricity to a 2,900 square-mile service area and about 984,000 customers. The entire service area is in the Greater Phoenix metro area, although the rapidly expanding cities of the metro area often have only portions of their incorporated territory served by SRP water, which must remain in the 1937 irrigation district and not used outside those boundaries. The SRP electrical service area is not restricted to the irrigation district and is therefore much larger in size, encompassing over a million customer accounts in 2018. The total amount of electricity sold by SRP was 33,567 GWh

(2014). Twelve Generation Stations, eight dams and renewable energy sources contribute to SRP's power sources. In addition, SRP receives hydroelectricity from Hoover Dam, Glen Canyon Dam and Parker Dam from WAPA (Western Area Power Administration) through power purchase contracts. SRP owns or co-owns fourteen thermal generation stations that use about 69 billion gallons of water annually (Diehl and Harris, 2014). The sewage effluent which is the cooling water resource for Palo Verde Nuclear Power plant is purchased from the 91st Avenue Wastewater Treatment Plant in Phoenix. The Wastewater Treatment provides annually around 26 billion gallons of treated effluent to Palo Verde Nuclear Power plant that is the only nuclear power plant using treated effluent. The effluent comes from the cities of Glendale, Mesa, Phoenix, Scottsdale and Tempe (Heiser, 2010; Wong & Johnston, 2014).

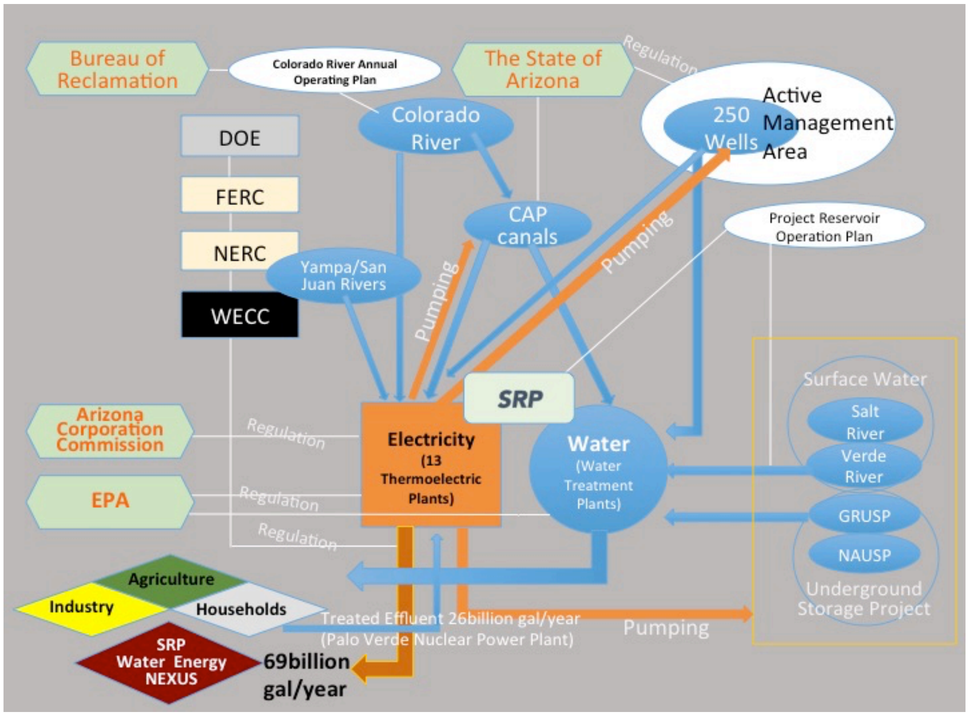

Figure 22. Water-Energy nexus in SRP (source: Changdeok Gim, author)

6.4 Unbundling Threads

Section 6.4 briefly introduces the institutional threads (e.g., vertical, lateral, and longitudinal) of Arizona's water and energy systems.

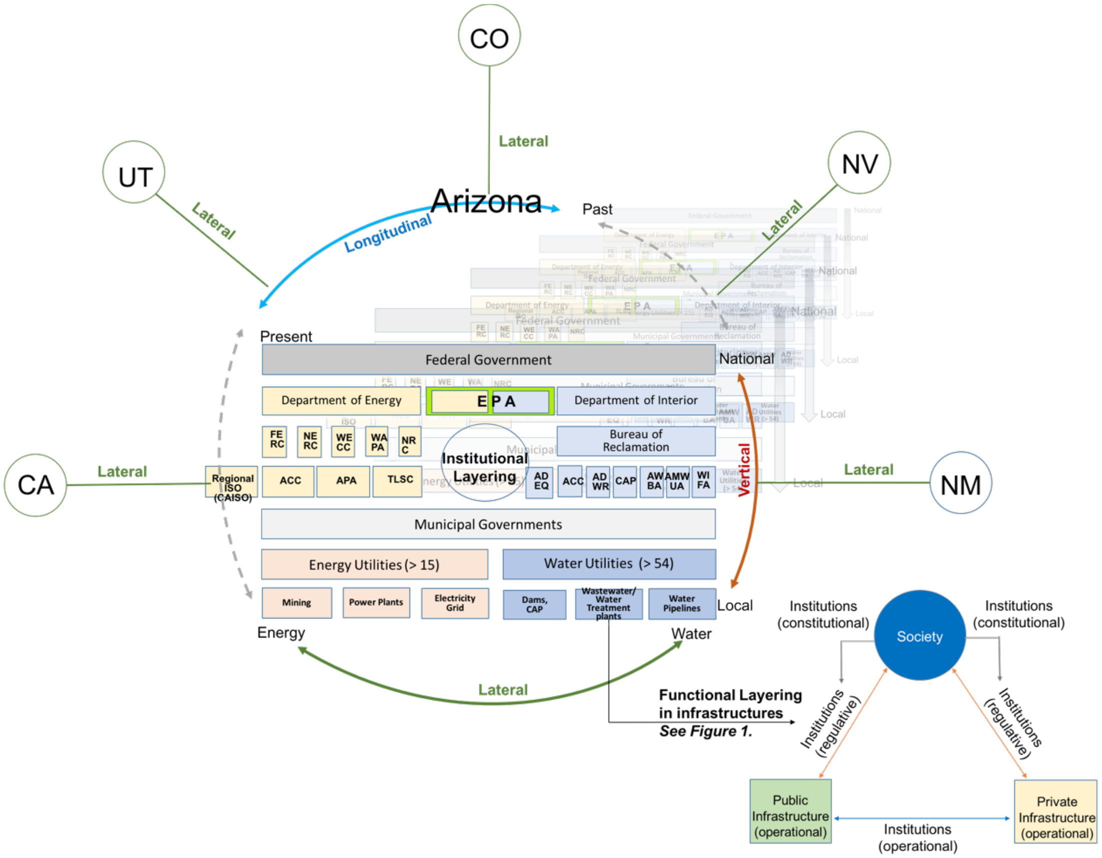

Figure 23. Three types of institutional threads (vertical, lateral, and longitudinal) of water and energy systems in Arizona that complicates infrastructure resilience (source: Changdeok Gim, author)

* This diagram is based on Alylott's (2014) water and energy systems in the UK. Author (Changdeok Gim) added the lateral, longitudinal, vertical, and functional threads of institutions.

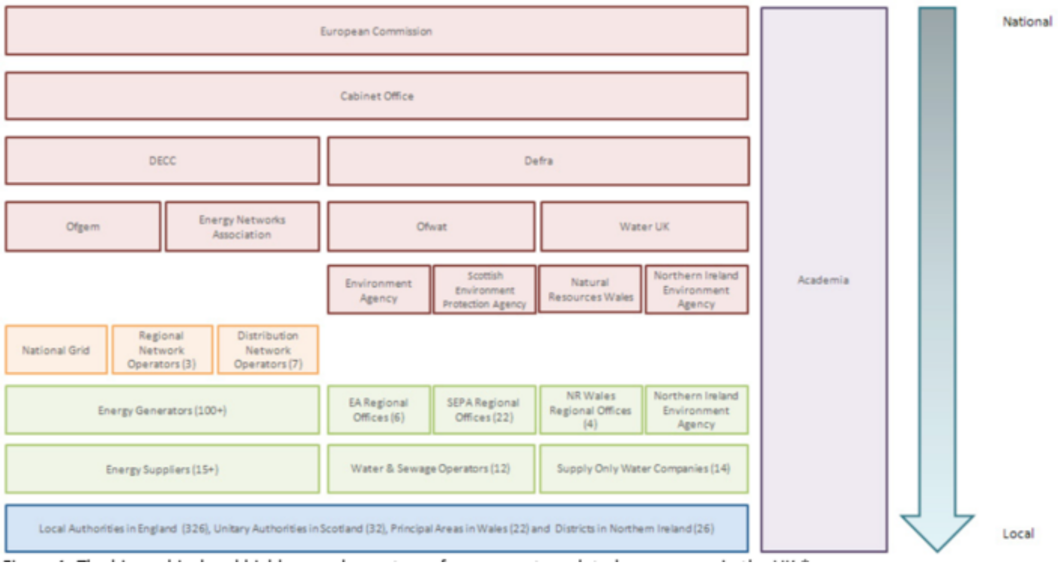

Figure 24. The hierarchical and highly complex system of WEN governance in the UK (source: Alylott, 2014)

6.4.1 Vertical threads

Despite the federalism of the United States, the examples of hierarchical order in water and energy infrastructures abound. The Bureau of Reclamation has the responsibility to decide whether to declare a 'shortage' on the allocation of Colorado River water for the next year. This ruling vertically affects the subsequent decision making of lower organizations and units, which are lower basin states, municipalities, and utilities through vertical threads. The decision and anticipation of water availability of Lake Mead from the Bureau of Reclamation vertically put pressure on the operational planning of municipalities for the next year's water in Arizona.

With respect to energy systems, a multitude of federal regulations are related to electricity demands, reliable supplies, reasonable rates, CO_2 emission reduction, outage anticipation, enhancing human performances, and preparation for climate extremes (DOE

2009; 2015a; 2015b). Regulatory institutions are mediating social needs and utilities' social and economic purposes. For instance, the Federal Energy Regulatory Commission (FERC), the North American Reliability Corporation (NERC), and the Western Electricity Coordinating Council (WECC) vertically set the transmission, distribution standards/quality. At the state level, the responsibility to implement these rules established by FERC, NERC, and WECC falls on the Arizona Corporation Commission (ACC). The ACC also deals with revenue requirements, resource acquisition, securities issuance, affiliated interests, service standards (e.g. standards for voltage, frequency, and other technical requirements, distribution service) and quality for the operation of energy infrastructures (Lazar, 2016).

In addition, the Salt River Project (SRP) in Arizona vertically governs both water and energy subsystems. The SRP board members, whom landowners elect, govern the water and electricity supply in the Salt River Reservoir District. The Salt River Valley Water User's Association (the Association), as a private water corporation, and the Salt River Project Agricultural Improvement and Power District (the District), as a public utility, are institutionally interdependent while serving the same service area, the Salt River Reservoir District. The administrative departments for each service are different but cooperate as well as coordinate within a mutual organization, SRP. Also, the Environmental Protection Agency (EPA) regulates not only the quality of different resources (e.g., air and water) with diversified institutions, but the regulatory sub-departments on air, water, and land as a higher organization (see **Fig. 25**).

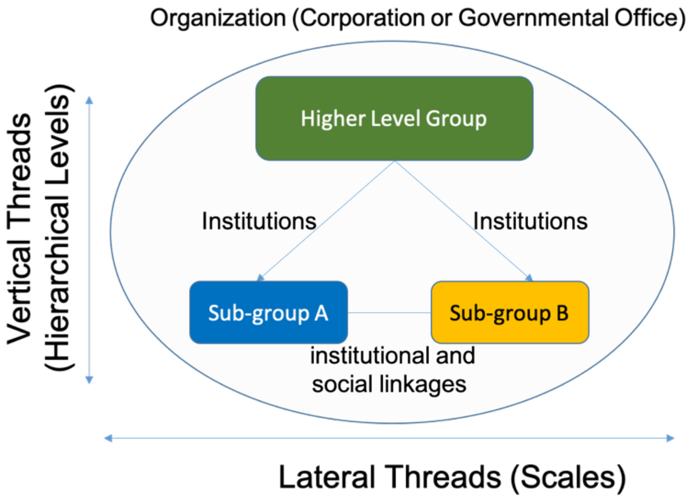

Figure 25. One organization and sub-groups (source: Changdeok Gim, author)

6.4.2 Lateral threads

The delivery of Colorado River water to the Phoenix area needs the cooperation of diverse water-related organizations such as the Supreme Court, the Bureau of Reclamation, the EPA, CAWCD, ADEQ, ADWR, Maricopa County, the City of Phoenix, and a water and electric utility, SRP (Salt River Project). Each organization has an expertise and knowledge system to deal with water delivery. Regarding water allocation, the Supreme Court makes decisions about water rights and the Bureau of Reclamation establishes the allocation scheme for Colorado River water. CAP canals should be successfully operated and maintained to deliver Colorado River water from Lake Havasu down to Tucson. Municipalities' and SRP's operation and maintenance for each component of the water system in the Phoenix area are also imperative to water delivery. The expertise of the EPA, ADEQ, and ACC (Arizona Corporation Commission) on water quality standards and price determine the quality of water delivery service. The lateral cooperation of these diverse human activities contributes to the resilience of the water system.

Furthermore, the water and energy nexus in Arizona unveils a more complex *lateral* coupled infrastructure and, in turn, institutions. APS, which supplies electricity for the Phoenix Metropolitan area uses a *lateral* spectrum of water resources for cooling—effluent, surface water, and groundwater—for cooling the electricity generators of APS's ten power generating stations (APS, 2015). Thus, the 'Shortage' declaration by the Bureau of Reclamation can affect the electricity generation of a thermoelectric power plant dependent on lower priority Colorado River water for cooling. Similarly, other users of Colorado River water can be more or less affected by the 'Shortage' declaration depending on their priority level, ranging from first (or the highest) to sixth (or the lowest). In 2012, an APS thermoelectric power plant, which uses CAP water with lower priorities (the fifth or the sixth) for cooling generators, had to secure alternative water resources through institutional coordination such as a new contract for water right exchanges (*personal communication, August 17, 2015*). This complex, *lateral*, and institutional layering in water and energy systems provides a space wherein each system indirectly intervenes the counterpart.

Specifically, the water system's groundwater regulations from the Arizona Department of Water Resources (ADWR) can directly govern the operational level institutions of power plants in Arizona, which use groundwater as their cooling water resource. The water department affects energy systems. If the ADWR's groundwater regulations reduce the amount of water that power plants pump out due to groundwater depletion, power plants in the energy system should find an alternative water resource in the water system, which does not include wells (direct intervention, **Fig. 26**). In a different case, water utilities and regulatory entities can increase the price of cooling water, and this will have a socially indirect impact on the operation of power plants. The increased water price indirectly affects not only the economy of electricity utilities but also general consumers' yearly budget.

6.4.3 Longitudinal threads

The delivery of Colorado River water requires political negotiations on allocation between stakeholders that constantly adapt to water users' needs (e.g., the Colorado River compact in 1922 and the update of this compact, namely the 2007 Interim Guidelines for drought seasons between California, Arizona, Nevada, and Mexico, and between stakeholders in Arizona). Since the Colorado River Compact in 1922, Arizona has held the entitlements for 2.8 MAF of Colorado River water based on the Law of the River (MacDonnell et al., 1995). However, the definition of Colorado River water consumption has longitudinally changed in terms of whether and how the 'consumption' includes all diversions of Colorado River water. Pursuant to the Boulder Canyon Project Act of 1928, Section 5 and Consolidated Decree by U.S. Supreme Court decision in *Arizona v. California*, 547 U.S. 150 (2006), the consumption of Colorado River water includes diverse uses of Colorado River water, such as the withdrawal of groundwater from the Colorado River aquifer 'Subflow Zone' (Robison et al. 2012; USBR 2010).

Another illustration of longitudinal changes in institutions is the 2007 Interim Guidelines to cope with drought. In 2007, California, Arizona, Nevada, and Mexico extended water allocation governance to establish a sophisticated scheme to share the shortage of Colorado River water in response to droughts in the Lower Basin to enhance the resilience of water and energy systems in the Southwest. According to the 2007 Interim Guidelines, the state of Arizona will take reductions of 320,000 AF when the projected elevation of Lake Mead on January 1st is below 1,075 feet elevation (CAP 2014, Grant 2008 pp.971-972). Given these longitudinal backdrops, a consent-based reduction strategy for Colorado River water allocation instead of a top-down program, once the lake level drops under 1,025 feet, should be prioritized in preparation for climate extremes.

> The 1922 Colorado River Compact was set up based on data from the wettest period in history (Reisner, 1986, p.130).

> Between 1907 and 1917, however, the wettest period on record, the river had discharged nearly enough water to fill the reservoir during several years (…) (Reisner, 1986, p.130).

The gathered data and sociotechnical fashion of overallocation in 1920s resulted in ‘structural deficit’ in relation to the allocation of Colorado River water since the ratification of the 1922 Colorado River Compact (Hirt et al., 2017). Longitudinal trade-offs between different generations have contributed to ‘structural deficit’ at the expense of the sustainability of the Colorado River.

6.5 Resilience Work of Institutions: Droughts and Energy-Water Infrastructures in AZ

The following sections will describe how resilience work of institutions, explained in Chapter 5, has sustained, adapted, and transformed infrastructure in Arizona.

6.5.1 Droughts and energy-water nexus in Arizona

The scope of case studies is limited to droughts and their impacts on energy-water nexus in Arizona for two reasons. First, for over a hundred years, Arizona has undertaken a chronic disaster, *droughts* since the formulation of water and energy systems in the 1900s. Among other disasters including earthquakes, hurricanes, tornados, and snowstorms, the sustainable management and expansion of infrastructures in Arizona have critically hinged on how to institutionally deal with droughts, which are “the most costly weather-related events” (NOAA, 2012). The secular risks of droughts on energy-water infrastructures have been termed by technical and social factors: controlling water fluctuations, regulating water consumption, and increasing water demands as the population grows.

Secondly, given lacking water resources, in Arizona, not only water systems but also energy systems have crucially relied on water governance for the availability of cooling resources: water. Thus, energy-water resiliencies in Arizona is more tightly intertwined than any other states in the US. A wide array of water scarcity issues have simultaneously challenged both water and energy infrastructures over time. Flattening intermittent water inflows, adapting regulations for water sustainability, and transforming the landscapes of water systems have been tightly connected to the resilience of energy systems. In particular, operating daily and monthly water inflows to fill dams and to generate hydroelectricity, regulating water consumption of electricity utilities, and constituting new water-energy landscapes and burdens of future water shortage between states anticipating Colorado River water shortages have all challenged both systems' resiliencies. Therefore, discussion on infrastructure resilience to droughts necessarily leads to the investigation on the coupled energy-water nexus in Arizona. According to the Arizona Department of Water Resources (ADWR), Arizona currently undergoes one of the most draconian drought seasons since the 1900s (City of Phoenix, 2011, p.45, Fig. 4-2).

6.5.2 An institutional tree of energy-water nexus in the Phoenix Metro Area (PMA)

To conduct institutional analysis on resilience work, first, this research mapped out a current institutional tree of water and energy systems (**Fig. 21**) with qualitative data from semi-structured interviews with over 30 experts at water and energy systems as well as literature reviews based on our framework in Section. The following sections briefly sketch how institutions and organizations stably operate, adaptively regulate, and innovatively transform water and energy systems in the PMA. The operation of Salt River Project (SRP) and other utility level organizations work on operational stability and routinized work, whereas regulatory entities such as Arizona Corporation Commission

(ACC), Arizona Power Plant and Transmission Line Siting Committee (TLSC), and ADWR focus on the regulatory adaptiveness (correction) role. Federal level organizations, such as the Supreme Court, United States Bureau of Reclamation (USBR), Environmental Protection Agency (EPA), and Department of Energy (DOE) guide long-term political constitution rather than specific operational practices or regulatory adaptation.

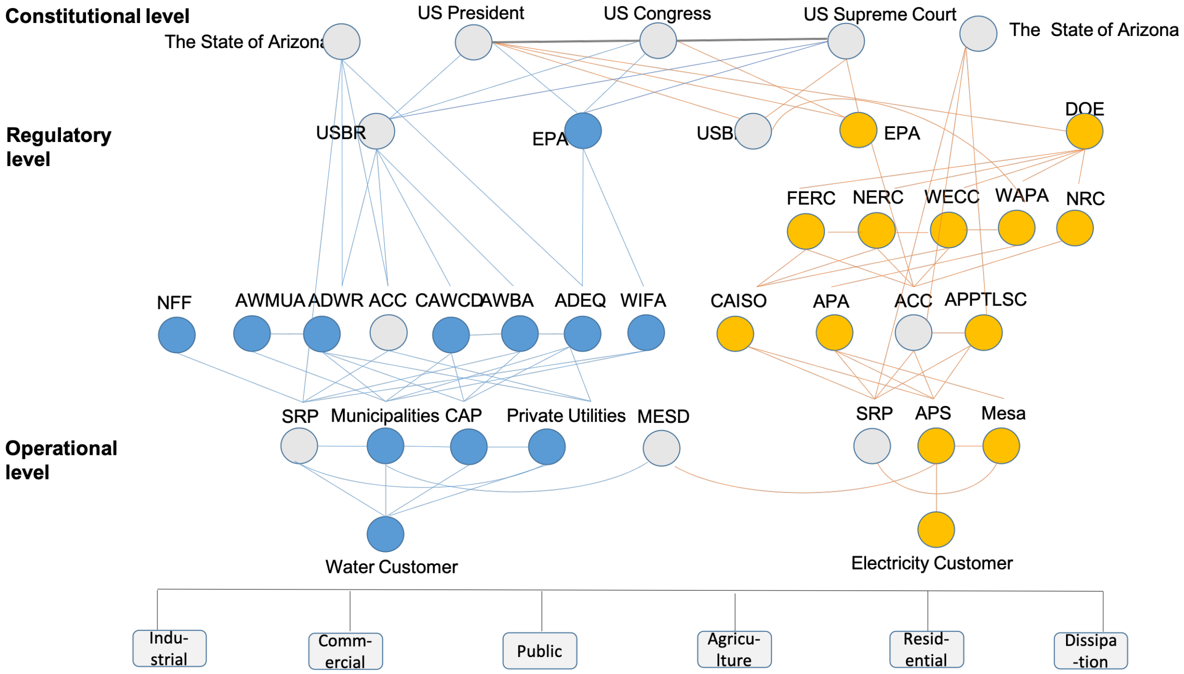

Figure 26. The organizational and institutional network trees of water and energy systems in the PMA (source: Changdeok Gim, author)

The following sections discuss how operational, regulatory, and constitutional institutions have served on the resilience—following the resilience definition in this chapter—of water and energy infrastructures responding to water shortage. In Arizona, water and energy systems are institutionally interdependent in three ways: vertically, laterally, and longitudinally. Moreover, continuous, occurring trade-offs are mediated through these interdependencies.

6.5.3 Operational, regulatory, and constitutional work of institutions for the resilience of energy-water nexus in the PMA

Table 5 summarizes the dynamic resilience work of institutions of water and energy systems in response to water availability issues in the PMA at different levels and scales based on the analysis of institutional tree in **Fig. 21**. This section investigates how operational, regulatory, and constitutional institutions work on different functions, governance goals, uncertainties, and organizations for infrastructure resilience at different temporal scales.

Table 5. Resilience work by different types of institutions in the PMA

Dimensions	Temporal Cycles	Functions	Governance Goal	Uncertainties	Related Organizational Levels
Types of Institutions					
Operational	Minutes to months	Sustaining (e.g., SRP's prop program/ Annual Operational Plan for Hoover Dam)	Resilience of engineered infrastructure facilities (e.g., water supply)	Technical: daily or monthly water inflow, precipitation, temperature, daily electricity demands etc.	Water and energy utilities (e.g., Power Plants, Dams, Canals, and Transmission lines of SRP, APS, and City of Mesa)
Regulatory	Months to years	Adapting	Resilience of infrastructure	- Regulatory uncertainties	Municipalities, states, and

		(e.g., 1980 Groundwater Management Act/ RPS regulations)	as socio-eco-technical systems (e.g., groundwater sustainability)	within “a clearly defined boundary” - 1980 Groundwater Management Act / Water Banking System / ACC’s regulatory decision making	federal regulatory organizations (e.g., City of Phoenix/City of Mesa/ ACC/FERC/NERC/EPA)
Constitutional	Years to decades	Transforming (e.g., CAP canals, Colorado River water reallocation)	Resilience of societies (e.g., the resilience of Colorado River Basin states)	Long-term inflow changes on the Colorado River / social or political uncertainties (e.g., population growth)	State and federal political institutions and agreements (e.g., 1922 Colorado River Compact and 2007 Interim Guideline supported and legitimized by Congress and Supreme Court)

6.5.3.1 Operational work

Water utilities (e.g., SRP) regularly assess the accomplishment of a fixed goal, the stability of water outflow while controlling daily and monthly water fluctuations responding to intermittent water inflow. A water and energy utility, SRP adjusts, every six months or at least one and a half years, their PROP program (Project Reservoir Operation Plan), a computational modeling. SRP ’s PROP operates seven dams and approximately 250 wells, for the optimization of water release and hydropower generation (Phillips et al., 2009). Using the PROP system and other sensing facilities, SRP inputs many quantified numbers (e.g., precipitation, water demands, electricity demands, water inflow, and temperatures) to optimize water release and hydropower generation. The optimization of these technically identified numbers targets specific operational goals for six months. Hourly and daily fluctuations of water inflows and other variables calculated by modeling are statistically within the normal distribution curve of operation and a steady cycle of SRP's operational practices. Conventional engineering assessment approaches are employed in sustaining daily and monthly routinized practices, the PROP system and modeling for SRP's infrastructures (e.g., dams and grids).

Another case shows the operational resilience goal for stability at the expense of groundwater sustainability that state-level regulatory organizations pursue. In 2003, SRP's seven reservoirs including Roosevelt Dam and lakes could not water demands due to severe droughts (City of Phoenix, 2011, p.14). SRP's water supply mix is typically composed of approximately 900,000 acre-feet of surface water and 50,000 to 75,000 acre-feet of groundwater pumping (Phillips et al., 2009). However, in 2003, SRP changed the mixture of water resources and extracted approximately 200,000 acre-feet of groundwater which is twice more than typical pumping powered from SRP's 250 wells until August in 2003 (McKinnon, 2003). SRP's operational practices privileged a utility governance goal, water supply to customers over a broader socio-eco-technical resilience goal, groundwater sustainability, given no permission regulations on drilling by power plants outside AMA areas. In broader contexts, these operational practices render energy-water nexus less resilient.

6.5.3.2 Regulatory work

Municipalities, states, and federal regulatory organizations (e.g., City of Phoenix, Tucson, ACC, and ADWR) reconfigure and regulate socio-eco-technical infrastructures in the mid-term at the state or federal-level resilience context while reordering energy-water nexus. In February 2014, the city of Phoenix and Tucson made a water storage contract preparing for water shortage. With this agreement, the city of Phoenix became able to store their surplus CAP water in underground storage facilities owned by the city of Tucson. In severe droughts, the city of Phoenix can directly consume the CAP water allocated to the city of Tucson, without pumping out the stored water in Tucson's storage facilities. In turn, CAP water users in the city of Tucson will use the stored water in their facilities accrued from the surplus CAP water owned by the city of Phoenix (Megdal, S. et al., 2014). This institutional exchange illustrates an adaptive 'bounce forward' towards more energy efficient contingency nexus, a new status quo, to cope with droughts for years instead of holding an engineering fixed role of water canals and storage facilities.

Another example of regulatory work of institutions is the establishment of the 1980 Groundwater Management Act to regulate water consumption of electricity utilities in designated Active Management Areas (AMA). First, APS, an electricity utility, incorporated groundwater regulations for sustainability into their operational practices (**Fig. 14**). The cooling towers of the Palo Verde nuclear power plant, which is partially owned by the state's largest electric utility, APS, should discharge cooling water after over 15 cycles pursuant to "The Third Management Plan" of the 1980 Groundwater Management Act. Water regulations impact and adapt the operational cycle frequency of cooling water (Bracken et al., 2015). Secondly, the ACC and its Transmission Line Siting Committee (TLSC), regulating 15 energy utilities in Arizona, review and decide whether to permit the construction proposals of power plants which supply electricity to the PMA. In 2001 and 2010, the ACC rejected two construction proposals (Big Sandy Power Plant & Hualapai Valley Solar Project) which planned to consume groundwater (Bracken et al., 2015, p.56). The ACC maneuvered the nexus configurations to adapt them to an upper-level goal, the resilience of socio-eco-technical nexus.

6.5.3.3 Constitutional work

Federal-level interventions by USBR or US Congress transformed energy-water nexus in Arizona when uncertainties and tasks became over the jurisdictions of states. The CAP canal system (completed in 1993) supported by the Colorado River Basin Project Act of 1968 is an example which transformed the energy-water nexus landscape responding to increasing water demands by population growth in the PMA. The state of Arizona could not have full access to the entitlement of 2.8 MAF of Colorado River water since the 1922 Colorado River compact due to lack of access channels. The construction of CAP canals required a federal level political mediation due to litigation and contestations between Lower Basin states (e.g., California, Arizona, and Nevada). The 1968 Colorado River Basin Project Act confirmed the amount of Colorado River water to deliver, financed the construction cost, and facilitated the construction of transmission lines and the coal-fired Navajo Generating Station (NGS) in northern Arizona. The NGS was completed in 1976 to provide electricity (2900 GWh annually) to the 336 miles-long CAP canal to elevate Colorado River water up to 2,400 feet using 14 pumping stations. Currently, the CAP canal delivers approximately 1.6 MAF ($1MAF=1.2335 KM^3$) of Colorado River water from Lake Havasu to the Phoenix metro area, then to farmers in Pinal County, and ultimately to the city of Tucson (USBR 2010; CAP, 2011).

After the creation of transformational nexus of the CAP canal and the NGS in the 1970s, water systems underwent a sharper transformation in 2007 to overcome unclear meaning on burdens of respective states and stakeholders for ‘Colorado River water shortage.’ Overcalculation on Colorado River water inflow for the 1922 Compact resulted in ‘structural deficit’ of overallocation, and contestation between states around the Colorado River water shortage had been amplified (Hirt et al., 2017). After nearly 80 years of contestation, in 2007, Lower Basin states adopted a transformational plan, the 2007 Interim Guidelines (Kates et al., 2012), to overcome the supply/demand deficit by sharing shortages of Colorado River water in case of long-term droughts. However, this transformational change on sharing of future water shortage—the water reduction will be 320,000 AF on Arizona and 13,000 AF on Nevada when the Lake Mead level reaches the threshold elevation of 1,075 feet (AWBA, 2014). This challenged the operational practices of electricity utility, APS. Due to the junior status of water rights of Arizona, electricity utilities were under pressure to adapt and find alternative sources of water. For instance, APS contracted with the Gila River Indian community to purchase stored water for their thermoelectric power plant in preparation for the curtailment of ‘excess water’ in case of ‘shortage declaration’ by the US Bureau of Reclamation.

6.6 Conclusion

As observed in the case study in this chapter, operational, regulatory, and constitutional institutions have distinctively contributed to the stability, adaptability, and transformability of energy-water nexus in the PMA with different frameworks such as engineering resilience, resilience engineering, and general resilience. Operational institutions manage and assess daily water inflow/outflow for operational goals. The SRP manages their reservoirs with PROP systems for their six months or one-year planning. The state of Arizona identified the depletion of aquifers (sensing and anticipating), adapted their groundwater management institutions in 1980s (adapting), and has protected the resilience of socio-eco-technical systems of groundwater for decades (learning). Also, upper and lower basin states in the Colorado River basin have transformed the allocation of Colorado River water in response to droughts and 'structural deficit' in 2007 and in 2019 since the 1920 Colorado River Compact for the resilience of the West. Case studies in this chapter prove that infrastructures capable of sustaining, adapting, and transforming to complex biophysical or societal disturbances have accomplished sophisticated and anticipatory institutionalizations.

Next, Chapter 7 examines the interdependencies of infrastructures. For instance, water institutions have affected the resilience of energy systems in Arizona. Droughts, electricity generation turbines, cooling towers, and water governance are all intertwined in interdependent water and energy systems in Arizona. This chapter investigates the impact of Colorado River water shortage on the management of power plants of APS and the impact of changes in water regulations (e.g., water conservation and air quality) on the circulation and vaporization practices of cooling water in Palo Verde plant’s stacks.

CHAPTER 7

THE INTERDEPENDENCE ANALYSIS OF WATER AND ENERGY SYSTEMS IN ARIZONA

7.1 Introduction

Chapter 7 focuses on the institutional interconnection of the resilience work done by institutions across two different infrastructure systems: water and electricity systems. Water and energy systems are intertwined in Arizona. In traditional engineering approaches, interdependent infrastructures are typically analyzed in terms of their physical interconnections. Chapter 7 demonstrates that institutional interdependencies can also create resilience challenges. Compromises to one system (the energy system) can derive from the other system's domain (water governance) via institutions. The resilience work of one system affects the other's resilience. Chapter 7 sketches out how the water and energy systems of Arizona are laterally and vertically interlinked together via institutions in Arizona. For instance, a 'shortage declaration' on the Colorado River, which is a key element in the resilience work of water institutions in Arizona, can impact not only the management of water supply infrastructures but also the management of power plants, such as thermoelectric power plants that use diverse sources of water for cooling.

In detail, Chapter 7 investigates the adaptation and resilience work of water and electricity organizations and their impacts. For instance, after nearly 80 years of contestation, in 2007, Lower Basin states adopted a transformational plan, the 2007 Interim Guideline (Kates et al., 2012), to confirm the sharing shortages of Colorado River water in case of long-term droughts. These constitutional adjustments in water governance affect the operation and regulation of energy systems in Arizona. In 2014, due to the junior status of water rights of Arizona, electricity utilities were under pressure to adapt their practices. One electricity utility had to find an alternative water source, Gila River Indian community's stored water, for their thermoelectric power plant in preparation for the curtailment of 'excess water' from the CAP system in preparation for a 'shortage declaration' by the US Bureau of Reclamation. Analysis of these kinds of institutional interdependencies offers an important strategy for improving the electricity system's resilience work.

The second contribution of the case studies in Chapter 7 is to show the low visibility of institutional interdependencies. Institutional interdependencies of infrastructures are hard to identify without in depth institutional analyses. For instance, the relation between nuclear regulatory institutions in Japan and the productivity of US factories was not evident until the impact of the Fukushima nuclear disaster on Japanese automotive companies disrupted the supply chain of automotive industries in the US. Soft infrastructures (Eakin et al., 2017), which encompass institutional interdependence, are a common thread of infrastructure networks, which "become[s] visible upon breakdown" (Star, 1999, p. 382). Conducting institutional analyses as a part of infrastructural management can better equip infrastructure institutions to anticipate complex challenges which run through social and institutional networks.

7.2 Sociotechnical Interdependencies

The following sections use the sociotechnical approach to analyze the case of water and energy systems in Arizona in order to illustrate the implications of institutional interdependencies for infrastructure resilience. The case study shows that climate extremes not only degrade the physical capacity of infrastructure but also disrupt embedded institutional arrangements in society which are critical to infrastructural functionality, which is a focal point in this research. Just as in the example of the 2011 Japanese tsunami impacting the US economy via supply chains mentioned above (Nanto, Cooper, & Donnelli, 2011), climate stressors flow through the complex interdependencies of social and institutional networks to impact different facets of water and energy systems.

Section 7.2.1 and 7.2.2 then explores the effect of groundwater regulations and water governance changes on the operation of power plants which supplies electricity to the Phoenix Metropolitan Area (PMA). In particular, a couple of examples of utility companies' organizational adaptation in Arizona elucidate how sociotechnical disturbances in the water system globally influence the local operational performance of energy organizations from the systems theory perspective. Section 7.3 anticipates *future* institutional challenges, which are likely to be water shortage (i.e., 'Shortage Declaration' by Bureau of Reclamation) and its cascading effects, to the power system based on the institutional analysis of current water resources for power plants in the PMA. The effects of climatic changes on water availability will necessitate shifts in water-related institutional arrangements wherein power systems are fabricated with grids. These institutional shifts, which are vulnerabilities, will impact energy systems in Arizona and in turn the price of water and agriculture products in Arizona.

7.2.1 The institutional interdependence of water and energy systems in Arizona

The rest of the chapter will explore the challenges of institutional interdependence and infrastructural resilience through a sociotechnical systems analysis of the coupled water and energy systems that operate in the State of Arizona. Infrastructures including water and energy systems, nested in institutional arrangements, are vertically, laterally, and longitudinally connected via institutions, but how these threads formalize infrastructural interdependencies has been rarely discussed in previous studies. The following sections will reify the conception of institutional interdependence. In particular, this section illustrates how institutional threads are interwoven into interdependencies of infrastructures and how interdependencies put trade-offs in complex sociotechnical networks.

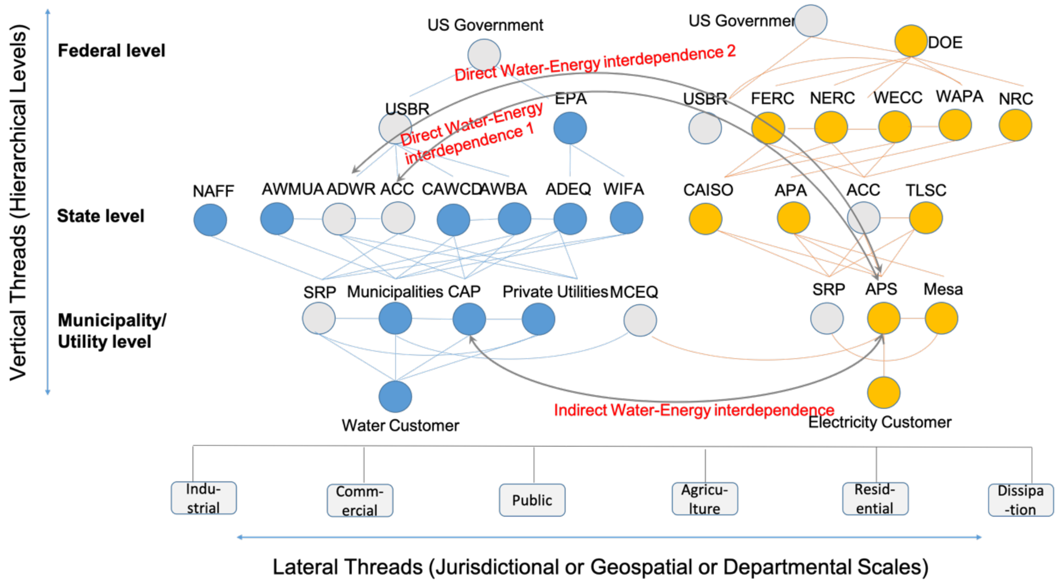

Figure 27. Institutional network trees of water and energy systems in the PMA (source: Changdeok Gim, author)

* Water and energy systems in Arizona are composed of multiple organizations at vertical levels and lateral scales. Lines points to interactive threads which diverse institutional arrangements govern these interactions. Blue color means water-related organizations, and orange color stands for the organizations of the energy system. Gray organizations are mutual agents in water and energy systems.

7.2.2 Direct institutional interdependence and trade-offs

This section will investigate how water system directly governs energy sources in Arizona. Direct governance means direct interventive actions on the operation and management of energy systems. For instance, in some cases, concerns on groundwater depletion and privileging water over energy compromised the construction of thermoelectric power plants in Arizona via regulatory interdependence. In particular, the Arizona Corporation Commission (ACC) and ADWR emphasize water conservation while shaping and balancing the relationship between water and energy systems (**Fig. 28**). Groundwater regulations of ADWR have significantly and directly affected the operation of power plants through interdependence grids. In terms of trade-offs, decision making between valuing water and securing electricity has long played a significant role as sociotechnical co-construction in designing water and energy systems in Arizona. These trade-offs for resilience have been negotiated and compromised through institutional interdependence.

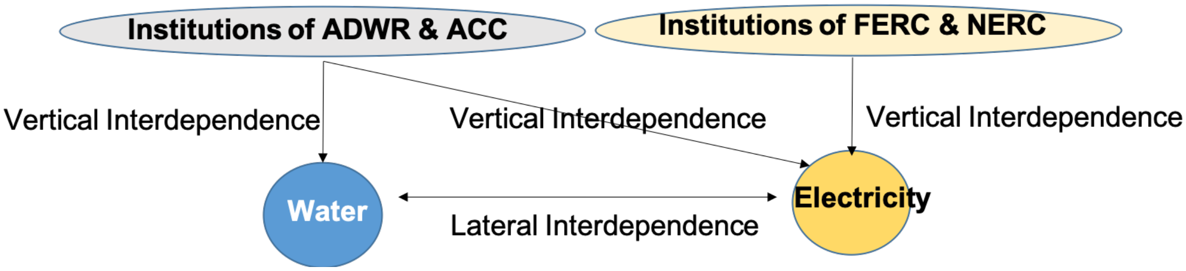

Figure 28. Direct intervention in AZ (source: Changdeok Gim, author)

7.2.2.1 Groundwater regulations and construction permission for power plants in Arizona

Institution 1: Article 6.2, 40-360.13. Certificate of environmental compatibility; availability of groundwater and impact on groundwater management plan

> For facilities subject to the requirements of this article within the service area of a city or town in an active management area, as such terms are used and defined in title 45, chapter 2, the power plant and transmission line siting committee shall consider, as a criterion for issuing a certificate of environmental compatibility, the availability of groundwater and the impact of the proposed use of groundwater on the management plan established under title 45, chapter 2, article 9 for the active management area (emphasis added).

Article 6.2 guides the certificate of environmental compatibility, which illustrates institutional interdependence with respect to the construction permission of power plants in Arizona. Article 6.2 directly regulate the operation and management of energy systems in Arizona (e.g., the construction of power plants). Water governance vertically directs the future planning and adaptation of energy systems through institutional interdependence.

In 2001, the proposal of a natural gas-fired 750 MW Big Sandy Power Plant by a New York based energy firm, Caithness LLC was rejected by the Transmission Line Siting Committee of the ACC (Title 40, Chapter 2, Article 6.2 of the Arizona Revised Statutes) indicating the groundwater consumption—from 2,400 to 2,500 gallons per minute—to cool generators in their operation plan (ADEQ, 2006; Natural Gas Intelligence, Dec. 3, 2001). In 2010, another case was also denied: the Hualapai Valley Solar Project, which presented a proposal aiming to construct a solar power plant. ACC required the utility to take into consideration for dry cooling generation turbines and the use of effluent water from the City of Kingman instead of groundwater pumping (Bracken et al., 2015, p.56). ACC reviewed the option of water “moratorium” for wet-cooling power plant projects in deciding the approval of the project (Bracken et al., 2015).

Two cases above show energy systems are directly regulated by water-related regulations in Arizona. ACC institutionally shaped water and energy systems with regulatory standards on groundwater consumption, which highlighted water conservation over energy system expansion. The containment of water demand (water security) and the growth of energy supply (energy security) come in need of resilient balancing trade-offs while shaping sociotechnical infrastructure in Arizona.

7.2.2.2 Water circulation regulations and the operation of cooling power plants

Institution 2: The Third Management Plan for Phoenix Active Management Area 6.5.4 Larger Scale Power Plant Program

“The Third Management plan requires that power plants in operation as of the end of 1984 achieve an annual average of 7 cycles of concentration in cooling towers, while facilities that went into operation after 1984 are required to achieve an annual average of 15 cycles of concentration in their cooling towers. (…) Facilities may apply to the director to use alternative conservation technologies in place of achieving 7 (or 15)

> cycles of concentration if the use of the proposed alternative technologies will result in equal or greater water savings. (…)”

A governance change, the Groundwater Management Act, which was established in 1980 to protect groundwater, has directly intervened and regulated the operation of energy systems. Since the 1980 Groundwater Management Act was set up, power plants in the Phoenix Active Management should circulate cooling water over 15 times in their cooling towers in pursuant to the Third Management Plan. Therefore, the cooling towers of the Palo Verde plant are also subject to the regulations of the Third Management Plan of ADWR, which regulates the circulation frequency of cooling water in pursuit of water conservation. The Palo Verde plant should discharge the cooling water after 15 cycles of water according to “The Third Management Plan” by ADWR (GAO, 2009, p. 59; Bracken et al., 2015, p. 33; ADEQ 2010, p. 14). The articles—6.5.4—of the Third Management Plan for Phoenix Active Management Area (2000-2010) regulate the “cycles of concentration” of water in the cooling tower (ADWR 1999, 6-57). According to the regulation, a large-scale power plant (over 25 MW electricity generation) using cooling water source should circulate the cooling water at least 15 times—7 times in the case of a power plant built before 1985—prior to blowing out vaporized water from cooling towers.

Currently, the Palo Verde plant circulates the cooling water over 20 times (Maulbetsch & Difilippo 2010, p.40; Henderson, P. et al. 2013, p.17). The problem with the circulation and vaporizing cooling is that as an electricity generation utility, the Palo

Verde power plant should abide by both water efficiency standards by ADWR and air quality regulation set by Maricopa County when circulating cooling water and discharging vaporized water through cooling towers (*personal communication, August 17, 2015*). If the EPA or Maricopa County sets out more stringent guidelines for the air quality, the cost for eliminating polluted components from vaporized water would be shifted to the private sector (private electricity utilities) (Middel et al. 2013, p. 17).

7.2.3 Indirect institutional interdependence and trade-offs

Unlike direct interdependence, the changes in water systems (e.g., water shortage and long-term drought) can indirectly affect energy systems in Arizona. Complex water governance and multiple resources, which is a characteristic of complex interdependence (Ostrom, 2010; Dui et al., 2010), has indirectly supported energy systems nested in water institutional arrangements. Higher lever water organization's decision changes the practices of low-level water organizations and in turn, cause the energy system's adaptations (**Fig. 29**). The two following cases of the Sundance Generating Station—a natural gas plant; located in Cooliage, AZ (Pinal AMA)—and the Yucca Power Plant of APS prove the detailed indirect linkages between water and energy systems and illustrate successful examples of the operational adaptations of power plants. Arizona Public Service (APS) altered their regular operation and management of water resources after considerable shifts in institutional governance, such as changes in allocation and water rights for the Colorado River water, stemming from considerations on water instability by the Bureau of Reclamation.

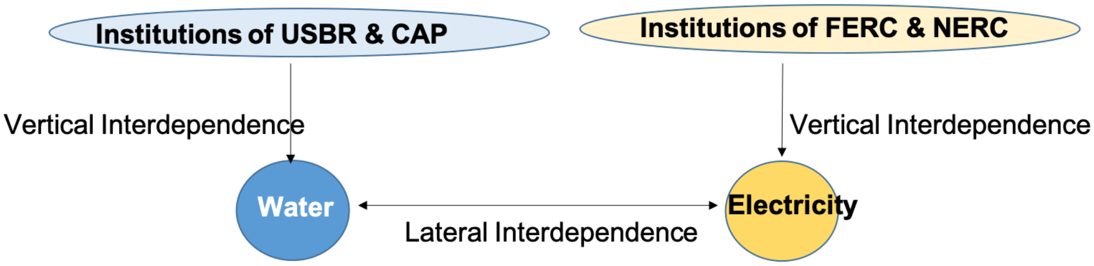

Figure 29. Indirect intervention in Arizona (source: Changdeok Gim, author)

7.2.3.1 Anticipatory adaptation of Sundance Generating Station (APS) to USBR's decision

The priority of the cooling water resource, which is an excess water supply for the Sundance Generating Station of APS, is relatively lower than the priorities of M&I subcontractors and Indian subcontractors in the Central Arizona Project system (CAP) (*personal communication, August 17, 2015*). In detail, the CAP system has its own unique priority system. The priority system is made up of four levels. The first level is the highest level, priority 3 level. Third priority means the water entitlement contract between the United States and water users was already executed on or before 1968 (USBR, n.d.) (68,400 AF). Indian consumptive water and Non-Indian Municipal & Industrial (M&I) are included in the second level (981,902 AF). Non-Indian Agricultural (NIA) consumptive water is situated on the third level (364,698 AF) (AWBA 2014, p. 29). As of 2014, there is no Non-Indian Agricultural subcontractor (CAP, 2014b). The fourth level is water for Agriculture (Ag) priority. The non-Indian Municipal & Industrial (M&I) water, Indian water, and Non-Indian Agricultural water are categorized as long-term contract water. The fourth and the other excess water usages are regarded as 'excess water' (**Fig. 30**) which has the lowest priority.

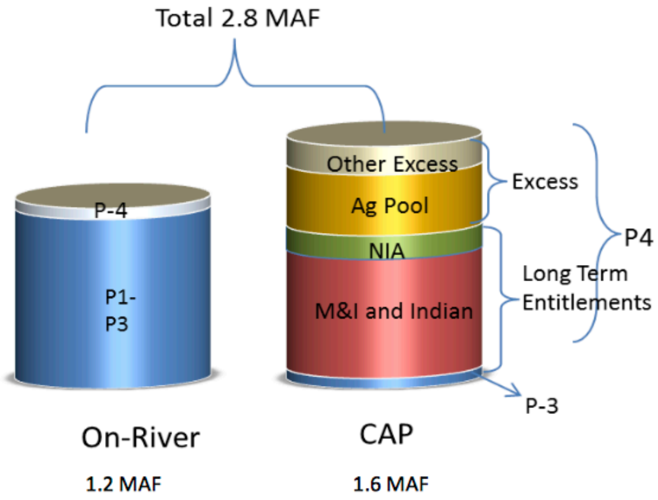

Figure 30. The Colorado River and CAP water priorities (source: AWBA, 2015)

Accordingly, in the declaration of 'shortage of Colorado River Reservoirs' by the Secretary of the Interior, the excess water should be reduced first, not the long-term subcontractors (about 1,415 MAF as of 2014)[18] (AWBA, 2014). Before 2012, there was a notice from the CAP board that the contract for excess water supply would not be renewed at some point due to the low elevation in Colorado River reservoirs. The most plausible option was finding an alternative water resource, otherwise there would not be sufficient water supply for the Sundance Generating Station within two or three years. Responding to this, the Sundance Generating Station of APS made an agreement with the Gila River Indian Community ("GRIC") which has higher priority in CAP water allocation structure and gave its Long-Term Storage Credits (LTSC) instead of the entitlement to get the CAP water directly. LTSC can be accrued from AWBA by storing unconsumed water in underground water storage facilities (AWBA, 2014). GRIC will use the transferred LTSC in pumping up the stored water at the recovery wells permitted by ADWR when they need to use that water (institutional exchange, **Fig. 31**). The average cost for recovery of LTSC was less than 60 dollars per acre-foot, as seen in the case of recovery by the California Metropolitan Water District (MWD) (AWBA, 2014, p.25; p.50).

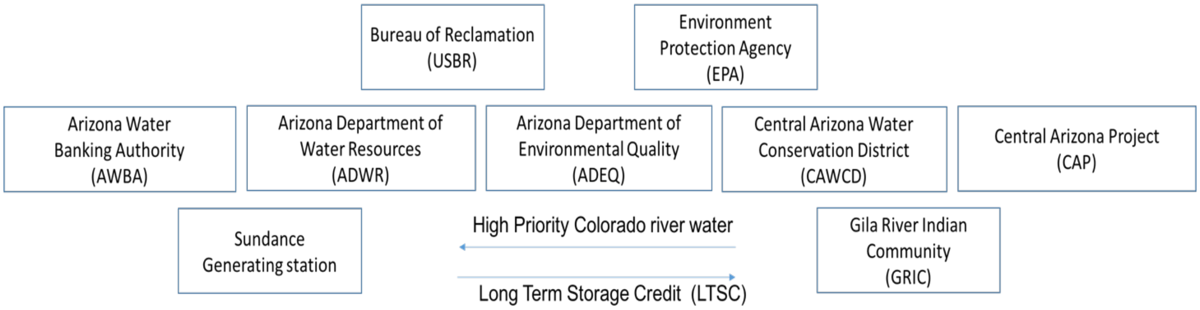

Figure 31. The organizational structure on water rights exchange (source: Changdeok Gim, author)

7.2.3.2 Governance of 'Subflow Zone' and Yucca Power Plant's (APS) adaptation

In the case of the Yucca Power Plant of APS, the significant problem was that APS had 5th or 6th priority, which is lower than CAP water, on the Colorado River water as cooling water resources. In 2012, APS was notified that their groundwater for cooling would not be available in a few years. APS believed that the Yucca Power plant, which had 1,500 AF of 5th/6th priority entitlement, had been using groundwater, not Colorado River water until the notice from the Bureau of Reclamation in 2012. However, in 2012, the Bureau of Reclamation identified and noticed that this groundwater used by APS from a subflow zone was not groundwater, but Colorado River water. Facing this institutional challenge, APS designated alternative groundwater resources (*personal communication, August 17, 2015*).

The major issue with groundwater consumption was that there was no priority rule in terms of groundwater pumping and, moreover, surface water and groundwater were hydrologically connected (Marder, 2009). With this respect, the Arizona Supreme Court developed a unique conception of "subflow" water defining it as "those waters which slowly find their way through the sand and gravel constituting the bed of the stream, or the lands under or immediately adjacent to the stream, and are themselves a part of the surface stream" in *Maricopa County Municipal Water Conservation District No. One v. Southwest Cotton* in 1931(Marder, 2009, p.191). More specifically, in September 2000, the Arizona Supreme Court confirmed the trial court's decision which further articulated the "subflow" zone. "All wells inside the saturated floodplain Holocene alluvium (subflow zone)" are presumed to be pumping subflow, not groundwater (Marder, 2009, p.192). Thus, water resources within subflow zones are not groundwater, but surface water.

In accordance with this constitutional governance, the Bureau of Reclamation pointed out that the location of wells, which supply cooling water, were inside the subflow zone in 2012. After the official notice by the Bureau of Reclamation, APS seeked for and designated alternative locations for drilling four new wells as cooling water sources. After this occurrence, APS has attempted to arrange a contingency plan for water resources of all the power plants. These narratives demonstrate the impacts of institutional shifts from water side on power plants, and system trade-offs and adaptation for the resilience of energy systems in Arizona. APS has begun to advance dynamic water efficiency assessments and standards for power plants. The Integrated Resource Plan reports of APS submitted to ACC clearly shows that APS makes efforts to lessen the consumption of water with their various types of turbines (e.g., coal-fire, natural gas, and nuclear turbines) (APS, 2016). Generation from natural gas turbines is the most efficient thermoelectric generator in terms of water consumption (Lamberton et al., 2010). However, the retrofit of contemporary coal-fire generators to natural gas power plants (e.g., the Ocotillo power plant of APS in Tempe, AZ) typically needs huge investments and is vulnerable to the fluctuations of natural gas prices. Moreover, natural gas fracking also shows lateral trade-off repercussions on the environment between geospatial areas in the U.S.

7.3 Anticipating the Institutional Impacts of 'Shortage Declaration' on Power Plants

In terms of long-term droughts, there was no specific operational guideline for operating Lake Powell and Lake Mead until the establishment of the 2007 Interim Guidelines. The Lower Division States did not have an agreement on the frequency or magnitude of any potential reductions in water supply. From 2000 to 2007, there had been the worst drought conditions ever, which led to reducing the Colorado River system storage. From October 1, 1999 through September 30, 2007, storage in Colorado River reservoirs decreased from 55.8 MAF (approximately 94 percent of capacity) to 32.1 MAF (approximately 54 percent of capacity). In 2004, the storage was 29.7 MAF (approximately 52 percent of capacity). These consecutive droughts led to a socially agreed upon standard, the 2007 Interim Guidelines for the low reservoir elevation of Lake Mead (U.S. Department of the Interior, 2007a; 2007b; 2010).

7.3.1 Shortage declaration: sociotechnical co-production of water governance

Declared droughts are a co-production of 'Law of the River' and the scientific anticipation of Lake Mead elevation for the next year. The Secretary of the Department of the Interior manages and operates Colorado River pursuant to the legal framework, 'Law of the River'. The legal framework governing Colorado river water comprises the Boulder Canyon Project Act of 1928, the Mexican Water Treaty of 1944, the 1963 Decision of the U.S. Supreme Court in *Arizona v. California*, the Colorado River Basin Project Act of 1968 (CRBPA), the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs of 1970, the Grand Canyon Protection Act of 1992, Lower Basin Water Banking Regulations of 1999, the 2006 Consolidated Decree of the U.S. Supreme Court in Arizona v. California, and other applicable federal laws (USBR, 2007b; 2010; Robison, 2012; USBR website).

Contrary to natural phenomena, the confirmation of 'a drought' is a socially constructed knowledge imbued with complex and political interactions between Arizona, Nevada, and California, and scientific modelling verification. Particularly, once the shortage of water supply is officially declared, the 2007 Interim Guideline comes into effect in Arizona. A confirmation about the elevation of Lake Mead is a result from the embedded knowledge order (Miller, 2008; Miller et al., 2011) with respect to the operation of Lake Mead. The number of elevation is the very indication for the Secretary's administrative declaration of a 'Drought.' The knowledge criteria for the declaration of droughts evidently reveal the interminglement of society and technoscience (Miller et al., 2011; Miller, 2017). "Such standards are never solely the product of pure science (whatever that might be) but always involve compromises among the industrial, the political, and the economic worlds" (Busch, 2013, pp.277-278). The definition and criteria of drought are socially constructed. "Co-production is an inevitable and ubiquitous feature of modern societies" (Miller & Wyborn, 2018). More importantly, 'Shortage Declaration' can beget ripple effects on further social arrangements and behaviors, such as the reduction of CAP excess water, the decrease of groundwater replenishment, and groundwater pumping in the Central Arizona area.

The deviations of institutional settings matter, not the amount of water consumed by power plants. In the case of the Secretary of Interior's shortage declaration, the state of Arizona should share the curtailments of the Colorado River water allocation as per the 2007 Interim Guidelines (CAP, 2014; the 2007 Interim Guidelines; Minute 319[19]; Arizona State Senate Issue Brief, 2015) (**Table 6**). A 'Shortage Declaration' will disturb basic institutional schemes governing water and affect the design of sociotechnical water and energy systems in Arizona. In terms of sectoral portions, the Agricultural sector uses 74% of Arizona water, Industrial 5%, and Municipal 21%. In terms of industrial consumption, the total amount of water consumed by thermoelectric power plants in Arizona was 170,250 AF (0.17 MAF) in 2008, which is a small fraction, approximately

2.5% (Bartos & Chester, 2015)—according to APS, 2010, this is 0.18 MAF. However, the institutional governance for 2.5% is not plain.

Table 6. The curtailment in 'Shortage Declaration' (source: CAP, 2014; the 2007 Interim Guidelines; Minute 319; Arizona State Senate Issue Brief, 2015)

Lake Mead elevation projection for the elevation on January 1st in August	Arizona	Nevada	California	Mexico
Below 1,075 feet (Tier1)	320,000 AF	13,000 AF	0	50,000 AF
Below 1,050 feet (Tier 2)	400,000 AF	17,000 AF	0	70,000 AF
Below 1,025 feet (Tier 3)	480,000 AF	20,000 AF	0	125,000 AF
Below 1,000 feet	Further measures will be taken. The Secretary of State will consult with the basin states. Consultations will begin if the elevation is below 1,000 feet.			

7.3.2 Cascading effects of a confirmed 'water shortage' on energy systems in the PMA

Institutional analysis on water and energy systems in the PMA emphasizes a distinctive aspect from the typical water and energy systems of the other states in the U.S., which are normally affected by the temperature of surface water (US DOE, 2014). In Arizona, the water-energy nexus has evolved into unique systems which are completely dependent on a cooler and consistent resource, *groundwater*. The uncertainty of surface water supplies and high temperature issues of water resources in Arizona, which is located in the Colorado River basin areas, make a unique system evolvement favorable for the static water resource, groundwater (USBR, 2016, p. 1-20).

Specifically, 16 of 20 total power plants of APS and SRP use effluent water or groundwater as cooling water sources (Diehl and Harris, 2014, Appendix 1; an ACC eDocket document # E-00000J-10-0053) for electricity supply in the PMA as of 2016. The surface water temperature of Yampa River, San Juan River and Lake Powell can be significantly related to the electricity generation efficiency in extreme heat. However, other power plants' water resources are not concerned with heat waves. APS wholly or partially owns 10 thermoelectric power plants and SRP owns 13 as of 2016. The Palo Verde plant, Navajo Generating Station, and Four Corners Power Plant are common power plants that both SRP and APS participate in. The following water resources are consumed as cooling sources by these power plants: surface water, effluent water, and groundwater. APS, which supplies electricity for water systems with SRP in the PMA, cool generators with multiple water resources—effluent (61%), surface water (21%), and groundwater (18%) as of 2010 (Arizona Public Service, 2010). In particular, surface water is used only for four power plants: the Hayden Generating Station (Yampa River), Four Corners Power Plant (San Juan River/ Morgan Lake), Craig Generating Station (Yampa River), and Navajo Generating Station (Colorado River, Lake Powell). Effluent water is used for the Palo Verde plant, Redhawk and Desert Basin Generating Stations for cooling. The Santan Generating Station and Kyrene Generating Station use CAP water. This CAP water means water is stored in the ground, not the surface CAP canal. The rest of the power plants are pumping groundwater from the aquifer. Thus, the temperature of surface water can affect only these four power plants (out of 20). In this regard, groundwater depletion draws attention with respect to climate change. The state of Arizona is one of the states in the U.S. which has experienced the severe depletion of groundwater according to USGS (2012) data. The amount of depleted groundwater for the last 100 years is approximately 102.0 km^3 as of 2008 (USGS, 2013, p.25).

Arizona is assumed to consume 2.8 MAF of groundwater annually in an unsustainable manner that dwindles natural water storages, aquifers in Arizona (Ferris et al., 2015, p.38). The Assured Water Supply program and the 1980 Groundwater Management Act have structurally endorsed the unstainable development of lands as well as the insufficient replenishment for aquifers at the expense of groundwater exploitation (Hirt et al., 2008; Megdal et al., 2014). Groundwater depletion is beyond the scope of the water-energy nexus, given the universality of water as a limited and non-fungible resource for industries (**Fig. 29**). Groundwater depletion has grown to be a complex socio-ecological-technical issue in Arizona. Historically, the state of Arizona has addressed the issue of water consumption by the agricultural sector, which consumes 4.4 MAF—approximately 70% of water available in Arizona—in multiple ways (ADWR website, n.d.). Yet this issue has been contentious in terms of water and Arizona's sustainability. Particularly, agriculture areas in central Arizona have been encouraged to use CAP water in lieu of groundwater since the official completion of CAP canals in 1992. CAP and municipalities agreed upon the subsidy policy program, the Agricultural Settlement Pool, for CAP water users in the central Arizona area. The price of water consumed by agriculture is lower than the official price of CAP water to encourage the consumption of Colorado River water (**Table 7**). CAP and municipalities were concerned that California could raise an issue on the incomplete use of Colorado River water, which was delivered through CAP canals (Bausch, 2015, p.748).

Table 7. Central Arizona Project Final 2015-2016 rate schedule

Various water users		2014 ($/ acre-foot)
Municipal and Industrial	Long Term Subcontract	146
	Non-Subcontract	166
	Recharge	166
	AWBA Interstate Recharge	189
Federal		146
Agricultural	Settlement Pool	67

(source: CAP webpage retrieved from http://www.mwdh2o.com/PDF%202016%20Background%20Materials/Central%20Arizona%20Project%202014-15%20and%202015-16.pdf)

7.3.3 Water-Energy-Agriculture interdependence and trade-offs

The following paragraphs will investigate complex interdependence and challenges to water-energy-agriculture.

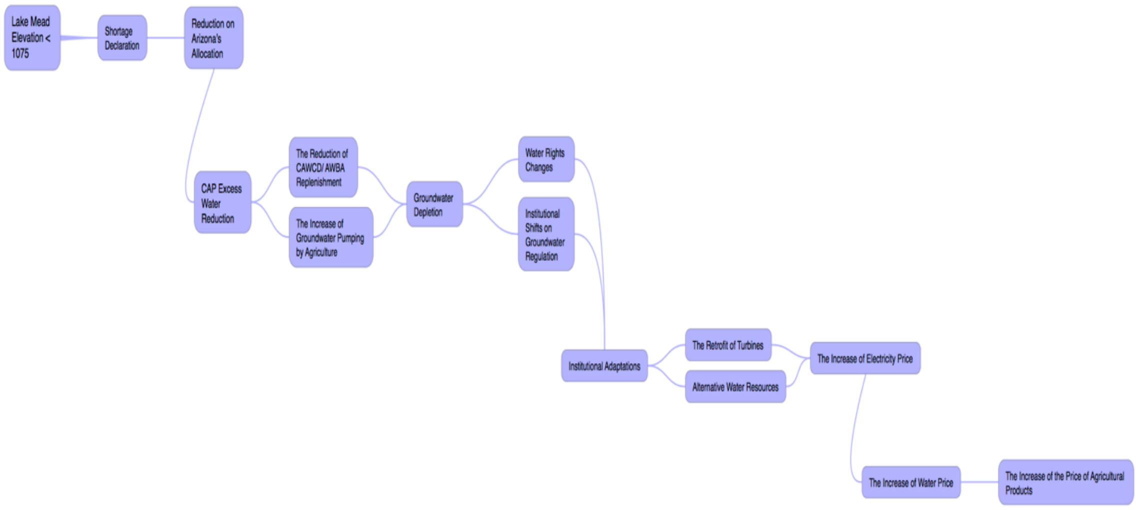

Figure 32. The cascades of a confirmed ‘drought’ impact on the Phoenix water-energy-agriculture (WEA) (source: Changdeok Gim, author)

Fig. 32 illustrates how confirmed institutional robustness such as a ‘**Shortage (drought) Declaration**’ based on **the Elevation of Lake Mead (<1,075 feet)** generates cascading effects via physical and institutional interdependencies over water-energy-agriculture systems in the PMA. ‘Declared droughts’ enhancing water robustness will affect physical water availability for thermoelectric power plants in Arizona. According to the 2007 Interim Guidelines, in the case of a Tier 1 shortage declaration (under 1,075 feet), the non-Indian agriculture water pool should be reduced by 143,000 AF (‘**CAP Excess Water Reduction**’). This curtailment (‘**Reduction in Arizona Allocation**’) can prompt the agriculture sector to return back to pumping groundwater **(‘The Increase of Groundwater Pumping by Agriculture’**) (CAP website, n.d.; Ferris et al., 2015). Using wells accelerates **‘Groundwater Depletion’**, and in turn stimulates **‘Institutional Shifts on Groundwater Management’** towards a tighter regulatory consensus (**‘Institutional**

Adaptations') to protect an irreplaceable natural resource, groundwater. Arguably, for desirable adaptation of whole water, energy, and agriculture systems, as seen in past cases of APS, these shifts demand anticipatory analysis while engaging diverse stakeholders as to socio-eco-agricultural trade-offs around the allocation and consumption of groundwater.

For instance, SRP's adaptation strategies have successfully managed drought risks and contributed to sustainable electricity and water delivery to the PMA for a century. However, with respect to climate extremes, SRP's several power plants will be in need of an innovative adaptation. Specifically, the Coronado, Springerville, and Coolidge Generating Stations of SRP are withdrawing groundwater outside AMA. There is no regulation of water rights on pumping groundwater outside AMA. However, tighter regulations on groundwater management in the area outside AMA could affect securing groundwater for these power plants. In other words, a newly amended 1980 Groundwater Management Act of ADWR can require water rights for the groundwater outside AMA (Ferris et al., 2015, p.23). In that case, these power plants need to secure **'Alternative Water Resources'** (or rights) or resources. Moreover, ADWR may not permit power plants to drill new wells which compromise sustainable groundwater management or other user's consumption in designating the sites of power plants as AMA due to draconian droughts (Ferris et al., 2015, p.47). Also, the updated groundwater regulations can require the withdrawers of groundwater to pay a withdrawal fee within AMA despite Grandfathered Groundwater Rights (Type I) affirmed by ADWR. In addition, other stakeholders such as local communities and the National Park Service are concerned about the long-term downsides of water pumping out on the C Aquifer, where the Cholla Generating Station is located (Whealan et al., 2003, p.14). These changes for the robustness of water resources will cause '**the Increase Electricity Price**' (Ferris et al., 2015), '**the Increase of Water Price**' and in turn '**the Increase of the Price of Agricultural Products**'. In Arizona, the price of water is a determinant factor to the economic growth and the sustainability of agriculture industries (*personal communication on Oct. 20th, 2017*).

7.4 Conclusion

On the theoretical basis of Chapter 2 to 4, Chapter 5 illustrated the history of sociotechnical fabrication of an infrastructure, Hoover Dam using the case study of water and electricity allocation. Chapter 4 showed that how the allocation of Colorado River water based on the Colorado River compact in 1922, Arizona's ratification of the Compact in 1944, the Supreme Court decision in Arizona vs. California in 1963, the negotiation between Arizona and California on the construction of the CAP canal in 1968—all these constitutional arrangements have been contributing to and adapted for the sociotechnical fabrication of Hoover Dam in Arizona. To broaden and deepen the research implications of sociotechnical perspectives and the redefinition of sociotechnical resilience in Chapter 2, 3, and 4, Chapter 6 empirically mapped out the institutional landscape of water and energy systems, unbundled institutional threads (e.g., the federal laws in Chapter 5) wrapping infrastructures, and illustrated the resilience work of different institutions dealing with a variety of uncertainties (technical and social uncertainties) in response to water disturbances to water-energy nexus.

Chapter 7 argues that direct or indirect reciprocal interactions between organizations through institutions need to be observed, analyzed, and anticipated with respect to infrastructure resilience in Arizona. The transformation of federal institutions adapts the state level regulations and design standards of infrastructure. Adapted regulations, in turn, change operational level check-up protocols, and manuals for management by organizations and technicians (e.g., the upgrades of protocols depending on the types of turbines) towards different technical and social practices. APS's "multi-layered approach to reduce water intensity," which includes air-cooled or dry-cooling generators, efficient water utilization, and renewable energy sources (APS, 2014), is an exemplary case of the resilient organizational knowledge adaptations responding to global droughts and water governance changes. The transition of coal-fired turbines to natural-gas is not only a technical or operational adaptation but also can be *constitutional*.

Anticipatory assessments on institutional feedback loops associated with water governance are critical to the resilience of power plants responding to climate extremes (e.g., 10-year droughts). Moreover, eighty percent of APS and SRP power plants are using groundwater for cooling, which fabricates a fundamentally different landscape of water and energy systems in the PMA from other states in the US. What is important should be the balanced institutionalization of trade-offs between multiple polities, stakeholders, and utilities. desirable claims, such as water security and energy stability while establishing multiple resilience strategies. Climate challenges to infrastructure pass through institutional webs while raising questions for trade-off dilemmas in institutions.

Reflexive balancing and trade-offs with engineering formulas are one of essential conditions that resilient infrastructure can be nurtured.

Therefore, the next chapter will investigate the complex risk and value landscape of water and energy systems, based on the risk innovation perspective by Maynard (2015) and the cultural theory of Douglas (1972). Nuanced resilience politics over entangled sociotechnical infrastructure is critically important to infrastructure resilience given the complexity of institutional work and interdependencies. The consideration of diverse perspectives and values is the focal point of the next chapter. As such, this grave question for society is the research question of the next chapter: for whom, in what processes, and to what ends, infrastructure should be resilient?

CHAPTER 8

RISK INNOVATION AND RESILIENCE POLITICS IN ARIZONA: THE COMPLEX LANDSCAPE OF WATER-ENERGY-AGRICULTURE

8.1 Introduction

Based on the theoretical and empirical contributions of previous chapters, Chapter 8 focuses on how the 'risk innovation' framework can be used to unpack the complexity of threats and values in water-energy-agricultural interdependencies. Chapter 8 argues that a critical element in long-term resilience work is risk innovation work: understanding and managing risk landscapes, politics, and values within which the complex realities of resilience work (Chapter 6) and interdependencies (Chapter 7) are designed, fashioned, and negotiated by myriad infrastructural institutions. The 'risk innovation' framework scrutinizes resilience politics and values to understand the complexity of infrastructure interdependencies. Given the complex interdependencies of institutions and infrastructures, resilience questions often escalate to social and political conundrums. The pathways to addressing the 'wicked problems' of infrastructure resilience include not only deterministic quantifications but also participatory governance (Rittel & Webber, 1973; Kreuter et al., 2004; Maynard, 2015). A key contribution to the participatory governance of resilience politics should be an in-depth investigation of the diverse values and political tensions involved in interdependent infrastructure systems, which can be facilitated by the 'risk innovation' framework.

In particular, using risk innovation, this chapter illustrates how different values and resilience politics around water and energy systems in Arizona will be impacted by a 'shortage declaration' according to the 2007 Interim Guidelines and long-term droughts in the near future. This chapter critically examines the complex landscape of threats and values embedded in socio-technical water and energy systems through the ‘risk innovation’ lens (Maynard, 2015), coupled with ‘cultural theory’ (Douglas, 1973). The chapter describes the diverse, complex threats to different constituencies, such as utilities, farmers, governmental organizations, and non-profit environmental groups, which will flow through institutional interdependencies, and shows how these threats will require an extensive resilience work in interdependent water-energy-agriculture networks. A ‘shortage declaration’ will curtail the allocation of Colorado River water to Arizona which has junior water rights, and in turn prompt groundwater pumping in the agricultural sector. The grand transition in the water supply portfolio in Arizona will change local groundwater regulations and water contracts of power plants for using water. Different values (e.g., political leadership, lucrative business models, family economic security, and groundwater sustainability) should be somehow reconciled for the smooth adaptation and transformation of each different system. The take away from Chapter 8 is that risk innovation analyses have the potential to guide and facilitate the implementation of these long-term adaptations and transformations of infrastructures to changing contexts and new societal values.

8.2 The ‘Risk Innovation’ Perspective

The ‘risk innovation’ framework (Maynard, 2015), which defines risk as “a threat to existing or future value,” is convincing given both quantitative and qualitative features of risk and the limitation of scientific risk assessments. According to Maynard (2015), value can be variously defined depending on “personal, societal and organizational contexts” (Maynard, 2015, p.731). As Selznick stated (1996), “the most significant aspect of institutionalization is infusion with value beyond the technical requirements” (Selznick, 1996, p.271). Given that a prominent feature of an organization is ‘infused value’ in the organizational structure, values of constituencies provide preliminary standards to judge whether events or human actions should be confirmed as risks.

Moreover, given the limitations of scientific methods, risk is not just a quantified number, but also a value-laden judgment. At the most basic level, science has been regarded as an appropriate tool for legitimizing and implementing public policies to resolve social problems. For instance, scientific modeling has played out in preventing catastrophic natural disasters (e.g., floods prevention and hurricane predictions) (Pielke, 1999). However, scientific models, which pursue crisp numeric results, have proven to be insufficient in solving complex problems in that they include logical fallacies with errors propagating through their designed models (Oreskes, 1994). In brief, if a scientific modeling produces a predicted outcome, which is congruent with observed (empirical) data, the hypotheses of this scientific modeling could be verified and confirmed (Oreskes et al., 1994, p.643). However, this reductionist view on scientific predictions and verification logic for generalization include innate logical fallacies (Oreskes et al., 1994, p.642-643). Affirmed valid results cannot transition into the evidence of the physical generality. Even though A (a hypothesis is true) ⇒ B (the results will be consistent with empirical data) is true, logically, the existence of B cannot be interpreted as the evidence of A. As Popper (1968) maintained, we cannot induce 'a reality' from finite observed data (Oreskes et al., 1994; Sarewitz and Pielke, 2000).

Innate uncertainties and complexity in risks as well as logical fallacies in modern reductionism modelling justify a new paradigm of risk thinking, the *risk innovation* framework by Maynard (2015). However, what values should be chosen to render society vigilant to particular events or human actions is not clear in the discussion of risk innovation. Also, the way to summarize and reduce the wide spectrum of judgments by individuals and constituencies on the appraisal between threats (cost) and values (benefit) into an interim and singular social memorandum needs to be deliberated.

8.3 The Complex Risk Landscape of Water-Energy-Agriculture Systems in Arizona

In Arizona, the landscape of risks around water, energy, and agriculture systems are complex. Complex networks are comprised of particular organizations for each domain (water, energy, and agriculture). Besides utilities, governmental organizations and advocacy groups also abound while making claims for their own organizational goals. Mapping the complex landscape of infrastructure and institutions illustrates diversified imaginaries, myriad values, complicated regulations, and distinct protocols for institutional and physical infrastructure. Particularly, each constituency has different values, cultures, and cognition for risks (Douglas & Wildavsky, 1982; Thompson &

Schwartz, 1990; Kahan et al. 2008). This mapping work helps to understand the risk landscape of water-energy-agriculture nexus.

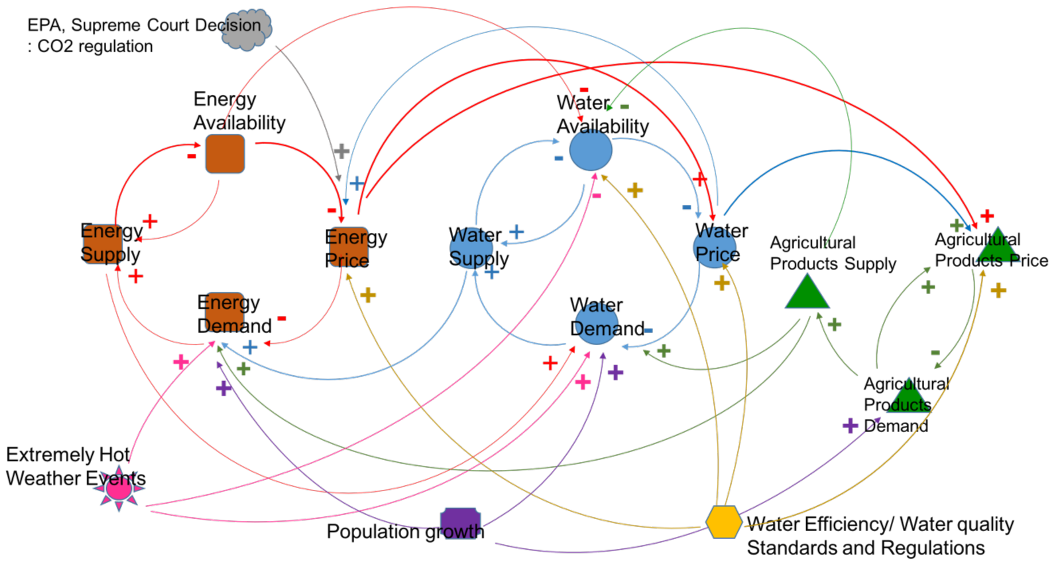

Figure 33. Water-Energy-Agriculture interdependence (source: Changdeok Gim, author; based on Senge and Sterman's (1992) system analysis)

Figure 33 and **Table 7** describes potential interdependent threats to the complex landscape of water and energy systems in Arizona, which include CO_2 regulations at the federal level, extreme hot weather events, population growth, and water quality/efficiency regulations, and the curtailment of the Colorado River water allocation (**'-' water availability**) due to the low level of the reservoir in Lake Mead according to the 2007 Interim Guideline. These threats can put a wide array of diverse influences and challenges to the values of different constituents. According to the 2007 Interim Guideline, in the case of water shortage, the state of Arizona should take the curtailment of 320,000 AF to their allocation, 7.5 MAF (million acre feet) (**Table 6**). How this shortage (**'-' in water availability**) and other threats (e.g., **CO_2 regulations**, **population growth**, **extreme hot weather** etc.) can affect diverse constituencies such as governmental organizations (the Environmental Protection Agency and ACC), farmers in the central Arizona area, environmentalists, and utilities (APS and SRP) will be a focal point in analyzing the complex landscape of water and energy systems in Arizona. Currently, approximately 4.4 MAF is consumed by the agriculture sector, which is equivalent to 70% of total water consumption in Arizona (ADWR website).

For instance, at the constitutional level, the demography change accompanied with **population growth** will affect the political landscape of Arizona. Typically, the population growth leads to **the increase of water and energy demand**, which in turn needs the expansion of water and energy supply systems (**'+' in water and energy supply**) and creates more ('+') demand **in energy and water**. Also, accordingly, the resurgence of CO_2 regulations at the federal level such as Clean Power Plan (Kirsten, E, 2015) and renewable source regulations (e.g., proposition 127) at the state level on power plants—e.g., Clean Power Plan, which was repealed by the EPA in October 2017—come to be an overwhelming institutional challenge such as the shutdown to the coal-fired power plants (**'+' in energy price**) in Arizona. For instance, the Navajo Generating Station (NGS), which is the third largest carbon emitting facility in the US (EPA, 2014), employs approximately 500 people from the Navajo Nation and from the Kayenta Mine where the NGS mines coal (azcentral, Sep. 29th, 2016). The shutdown of the NGS, which supplies electricity to the CAP canals, was not a simple decision (azcentral, Jan. 5th, 2017). The total electricity consumption for the 1.6 million AF (acre feet) CAP water delivery was approximately 2,800 GWh as of 2014 (Kleiman, 2016). That means the increase of electricity price necessarily cause **the increase of water price**.

Moreover, 86.2% of farms, which are largely dependent on CAP water in Arizona, are owned by families and approximately 80% of them are less than 50 acres. Most farmers in Arizona are struggling with their relatively low income, which means 85% of farms earn less than $25,000 dollars according to sale receipts data (Kerna, A. and Frisvold, G., 2014). These economic and cultural conditions generate repercussions **the increase of agricultural product price** and **the less consumption of agricultural products** which put negative impact on the income of agricultural households. Given the socio-eco-technical convolution of people's job, technology, regulations, and reverberating claims on clean energy, anticipatory governance on trade-offs is a social and political task, rather than quantification, in facilitating energy systems' transition in Arizona in Arizona.

8.4 Culture Theory

This chapter employs the culture theory to better analyze the values and cultures that defined the conception of risks in different communities. Given that organizational values are infused via institutionalization (Selznick, 1996), culture as a constitutional institution is a great locus to begin with an investigation on how risks are structured and what threats are harmful to what values of social constituents of water and energy systems in Arizona. Different cultural perspectives strongly affect the conceptualization and perception of risks (Slovic, 1987; Douglas & Mary, 1982). 'What is and what is not a risk' is a socially structured question (Beck, 1992). Kahan et al. (2008) analyzed different cultural cognitions (e.g., individualistic, hierarchical, egalitarian, and communitarian) of groups and found that cultural perspectives, not the extent of knowledge familiarity, are highly tied to different attitudes on risks and benefits of nanotechnology.

Organizations incorporate and react to threats via institutional structures: operational, regulatory, and constitutional (e.g., culture) threads. For instance, the drought risk (threat to value) in Arizona can be diversified into operational, regulatory, and constitutional threats (**Table 7**). Different constituents rely on the reservoir water of Lake Mead for different organizational values. Cultural cognition as a constitutional institution run through institutional grids and affect the formation of regulatory and technical risks. In other words, cultures contribute to the social construction of risks—i.e., via cultural cognition, particular threats are confirmed as risks with particular institutional arrangements—and other institutional sub-threats (regulatory and technical threats). Thus, to understand what infrastructure resilience means in Arizona, it is valuable to describe what diverse organizations' cultures look like and how these cultures contribute to the dynamic conformation of risks derived from climate threats (e.g., droughts to water and energy systems) with their particular institutional threads (Thompson & Schwartz, 1990).

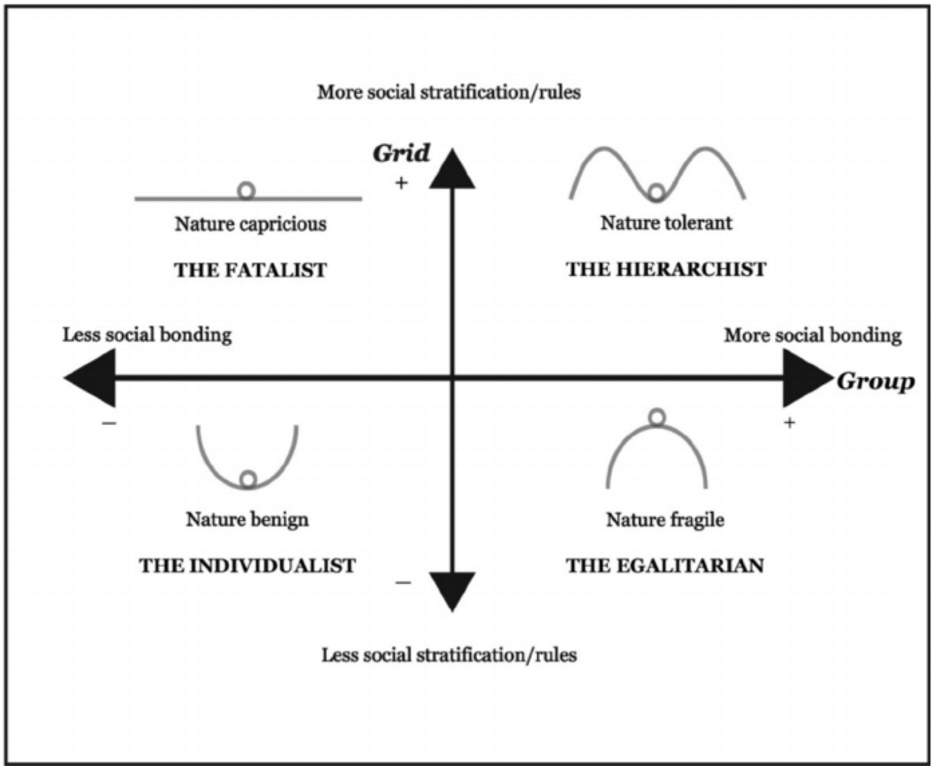

Figure 34. Four different perspectives on risks of the environment (source: Thompson & Schwartz, 1990)

In particular, Thompson and Schwartz (1990) divided organizations into four different types depending on their organizational structures' responses to different threats. The organizational structure of bonding and stratification affects the cultural perspectives of organizations, which in turn leads to different attitudes towards social, technical, and environmental threats to organizations. The framework by Thompson and Schwartz (1990) can be interpreted as a tool to understand different perspectives on constituencies' cultures and threats to these groups (**Table 7**).

Table 8. Threats derived from droughts and other threatened values

Constituents	Organizations incorporate threats and react to climate threats via institutional threads.			Threatened values
	Constitutional threats	Regulatory threats	Operational threats	
Government organizations (hierarchist)	- Negotiation of water allocation - The increase of social contestations/ litigation - Climate change - Population Growth	- Administrative pressure for the establishment of new regulations	- Wildfire suppression costs - Infrastructure upgrades subsidy	- Political leadership - Political stability
Agriculture - farmers (fatalist)	- Social concerns on groundwater depletion - The transition of land use	- Water rights change (e.g., well permission) - Water price increase - Electricity price increase	- Water quantity - Water quality - Electricity outage (due to heat waves)	- The sustainability of agriculture
Industry - water/ electricity utilities (individualist)	- Social preference on water efficient energy sources (renewable energy)	- Water price increase - Water efficiency regulation - GHG Emissions regulation (climate change regulations) - Groundwater regulations	- Water quantity (cooling water, water availability) - Water quality - Components failure	- Maximization of profit - The reliability of water/ electricity service
Environmentalists (egalitarian)	- Social conflicts - Unsustainable groundwater - Extreme weather events	- Social pressure for the establishment of new regulations	- The increase of unsustainable social practices	- The proliferation of social movement - Sustainability of society

8.4.1 Governmental organizations; hierarchist

From the perspective of governmental organizations, tolerant nature should be reinterpreted, reorganized, and managed by regulations (Thompson & Schwartz, 1990). Climate extremes prompt the introduction of new regulations (e.g., groundwater protection and CO_2 emission regulations). Federal level organizations (e.g., EPA) play an important role in establishing new regulations to respond to environmental threats to sustain their political leadership. The EPA is a federal government organization that has tended to address sociotechnical pollution threats with hierarchical regulatory frames since 1970 (e.g., the clean power plan program).

Arizona Corporation Commission (ACC) is a state-level governmental organization. Nature is under control of the ACC. The ACC is a key player in regulating water and energy dynamics in Arizona and focuses on adjusting water consumption by power plants. ACC regulates and reacts to water quantity threats with their regulatory permission on the construction of power plants. For instance, in 2001, the proposal to construct a natural gas-fired 750 MW Big Sandy Power Plant by a New York based energy firm, Caithness LLC, was denied by the Transmission Line Siting Committee of the ACC (Title 40, Chapter 2, Article 6.2 of the Arizona Revised Statutes), due to the groundwater consumption (2,400 to 2,500 gallons per minute) to cool generators in their operation plan. A caveat with this regulation is that the extent and contents of regulations for threats thoroughly rest in ACC's control. In this sense, nature is controllable.

8.4.2 Farmers in the central Arizona area: fatalist

Farmers typically stay outside of the discussion of water and energy systems in Arizona. The contestation around the water-energy-agriculture nexus in Arizona reveals this propensity. To farmers, nature is capricious.

> I looked at the front page of the Arizona Republic and there was another article about water issues, and after you read that so many times... I think Jesus, maybe it's time to get out... (Baushch et al., 2015, p.750)

The stability of water price plays a critical role in guarding the stable income of most farmers in Arizona. In Arizona, 86.2% of farms are owned by families and the average acreage of farms is smaller than that of the national average. Most farmers in Arizona are struggling with their relatively low income, which means the annual income of 79.7% farmers is under 10,000 dollars (Kerna, A. and Frisvold, G., 2014). The increase of water price due to droughts will significantly impinge on the sustainability of farms.

In fact, farmers do not use groundwater, not due to water rights but due to the pumping costs, which means CAP water is cheaper than groundwater (Bausch, 2015). The agriculture area in central Arizona has been using CAP water in lieu of groundwater since the official completion of CAP canals in 1992. CAP and municipalities agreed upon the subsidy policy program, the Agricultural Settlement Pool, for CAP water users in the central Arizona area (Bausch, 2015, p.748). The price of water consumed by agriculture is much lower than the official price of CAP water (**Table 7**). If there is a curtailment on

CAP excess water to agricultural sectors, there will be a regulatory threat to utilities in terms of groundwater regulations.

8.4.3 Utility companies: individualist

Nature is benign and resilient so are individualists' organizations. According to the water department, SRP has water rights for the 20 to 30 years of water supply contract for the water sources (*personal communication, September 4, 2015*). Climate change is not a new normal for SRP. Droughts have been the norm in Arizona (*personal communication, September 4, 2015*). Water resources for power plants are managed by the 'water rights management' department at SRP. Most power plants owned by the SRP use groundwater for cooling generators. The data about the exact amount of water consumption by power plants is not open to the public, though it could be approximately calculated from the types of turbines in use. SRP is exempted from the ACC's ruling by Arizona laws. For instance, SRP has no legal duty to submit the IRP report to the ACC. In this vein, when droughts disrupt the pre-existing governance on groundwater, this institutional disruption on water rights can threaten the current operation and management of water resources for power plants by SRP, which is different from SRP's individualistic conception of long-term droughts. Also, this disruption can give rise to social conflicts between stakeholders such as farmers, municipalities, local residents, and environmentalists.

8.4.4 Environmentalist: egalitarian

To environmentalists**,** nature is fragile. Threats such as air pollution and climate change are critical to the sustainability of nature from the egalitarian perspective. Sociotechnical systems embedded in environments should be careful about the harmfulness of their operation and management of nature. For instance, if climate extremes such as droughts cause the establishment of CO_2 regulations fueled by environmental movements who thinks 'nature is fragile', utilities (individualists) and governmental organizations (hierarchists) have to adjust their structures and practices to adapt to this new normality. The outcome of one entity's efforts can be a threat to the other entities' routines. For instance, the litigation between the EPA and the plaintiffs, such as the Sierra Club and the National Parks Conservation Association, demonstrates this dynamic complexity of risks landscape in Arizona. Environmentalists pushed governmental organizations and utilities to close the Navajo Generating Station (NGS), which supplies electricity to CAP canals. However, NGS employs about 1,000 people from the Navajo Nation and from Kayenta Mine, where NGS mines coal. Given the economic impact, the rescheduling of environmental regulations on NGS is not an easy risk assessment.

8.5 Conclusion

The theoretical contribution of Chapter 2, 3, and 4 is that these chapters pointed out and redefined a key aspect of infrastructure resilience as institutional capacities to sustain, adapt, and transform infrastructures to uncertainties and disruptions. Chapter 5, 6, and 7 respectively provided the supportive evidence of case studies illustrating three points: i) Hoover Dam as a sociotechnical infrastructure in Chapter 5, ii) the institutional landscape and threads of water and energy systems in Arizona as well as the resilience work of these operational, regulatory, and constitutional institutions in Chapter 6, iii) the resilience interdependencies of water and energy infrastructures via institutions in Chapter 7.

The focal point of this chapter is not about how to precisely measure risks, but how to make an orchestration of diverse constituencies' (e.g., hierarchist, individualist, egalitarian, and fatalist) cultural values with the risk innovation framework. Risk innovation as a risk politics methodology cares about human and social dimensions of risks. Risk innovation has the potential to open up hidden complexity of resilience landscapes and valuable opportunities for stakeholders. When muddling through and minute failures are encouraged, serendipity can be found at the destination. Wicked (complex) problems are not to be resolved, but to be agreed-upon. This is why plural *paradigms* still exist and will exist. Therefore, resilience is not just about risk assessments, but about risk innovation and politics.

Politics is never a panacea, but always a consequential determinant to social problems which are less linear or technical. Risk innovation to rigorous processes, reminiscent of Charles Lindblom's shrewd *incrementalism* (Lindblom, 1959), resonate with the queries in the introduction: *'To what extent, the repair, retrofit, and upgrades of physical structure can improve resilience?' 'Why is it worthwhile analyzing and anticipating institutional interdependence of infrastructures?'*

Finally, Chapter 9 expands and apply the interdependence and politics of resilience to a much broader context, socio-eco-technical infrastructure systems which means the water-energy-forest nexus in Arizona. In Arizona, the socio-eco-technical resilience of water, energy, and forests are tightly interdependent together. Wildfire incidents and the devastation of forests have detrimental impacts on both water-energy nexus in Arizona. Chapter 9 describes the forest policy transition as a resilience knowledge transition, knowledge processes, and socio-eco-technical boundaries work.

CHAPTER 9

FOREST MANAGEMENT AND INSTITUTIONAL TRANSITION

9.1 Introduction

Adding to the contributions of previous chapters, Chapter 9 suggests that resilience work is as much knowledge work as organizational work. The chapter identifies key knowledge capacities for organizations pursuing resilience: their abilities to monitor and observe, anticipate changes in, develop adaptive strategies for, and learn from experiences regarding socio-eco-technical systems, i.e., complex infrastructure assemblages and their networked relationships to ecological contexts in which social systems and services are managed. Arguably, as illustrated in the case study of forest management and its relations to water and electricity systems in Arizona, institutional transitions (resilience processes) are critical to the resilience of infrastructures. Regarding infrastructure and urban resilience in Arizona, the management of forests and wildfires is a crucial domain in which the inextricable nexus of water-energy-forest plays out. In this chapter, the process of urban resilience and anticipation will be understood and vetted through the procedures of long-term institutional transformation within which the dynamics of knowledge elements (e.g., contents, uncertainties, values, and epistemologies) formalize and take place.

In particular, decades ago, based on traditional engineering approaches to resilience, wildfires in forests were deemed as disturbances to be excluded. However, after observing severe wildfires, ecological failures, and disastrous devastation of forests, the old paradigm of 'fire control' was replaced by a new paradigm of 'fire management.' Fire management is not a *laissez-faire* policy, nor is it a purely engineered approach; rather it is a mixture of stability-oriented and flexibility-oriented approaches. Small and big wildfires occasionally caused turbid water resources and communication/electricity outages coupled with monsoon seasons. Recognizing this has helped legitimize an institutional transition from prioritizing dense forests to encouraging healthy (or thin) forests. This anticipatory recognition took decades and had to be supported by long-term preparatory planning, efforts to engage multi-stakeholders, the integration of a wide array of epistemologies, and the mediation of diverse organizational values.

9.2 Engineering Resilience, Water-Energy-Food Nexus, and Forest Management in Arizona

Until the 1990s, forest management was dominated mainly by the engineering resilience perspective: sustaining the minimization of wildfires and maximization of timber density. Scientific quantification and measurement emphasize one original steady state: dense forests. Engineering resilience perspective ignored local Native American knowledge which foregrounds the natural cycle of a frequent fire burning and a resilient density of ecosystems. Dense forests were deemed as a desirable state of forests, and the management was focused on planting more trees and sustaining the density (Arno, 1996a; 1996b).

More broadly, *scientific forestation* has proved to be perilous. The neglection of the complexity and openness of component interactions of ecosystems by scientific forestation has typically resulted in disastrous ecological failures and the death of forests in Europe and the United States in the early 1900s (Scott, 1998). Along with these fallacies in Europe and the US, engineered forestation and wildfire control prevailed in Arizona until the establishment of the Forest Health Advisory Council in 2003 (Governor's Forest Health Advisory and Oversight Councils, 2007). Wildfires, regardless of their intensity and scales, were conceived of as useless and harmful to the health of forests. However, ecologists have argued for the benefits of small natural wildfires to the ecology for decades.

Urban infrastructure interdependencies become complex when coupled with an ecological consideration of forest management. Since myriad technical and social components contribute to the creation of complex sociotechnical systems in urban areas, urban space is not a linear and quantifiable materialization, nor a closed system. Forests as an ecological infrastructure (Grabowski et al., 2017; Silva & Wheeler, 2017) are tightly interdependent with water and energy infrastructure in Arizona. Forests invisibly fill up reservoirs, while water resources and the outflow of reservoir water generate hydroelectricity. The management of forests affects ecological linkages and the physical resilience of water and energy systems in Arizona.

Urban infrastructures such as water, energy, and forest systems are interdependent and complex in Arizona. Thermoelectric power plants need water to cool, and water resources come from deep forests. In terms of Phoenix's water supply portfolio, the city of Phoenix prior to 1980 got about half its water from SRP and half from non-renewable groundwater pumping. Most of SRP's water supply comes from the snowpack of the 8.3 million acre watershed in northern Arizona. Healthy forests are linked to not only the quantity but also the quality of water sources in Arizona. SRP, a water and energy utility, has made efforts towards reforestation since 2010 in a partnership with the National Forest Foundation (NFF). Along with SRP's efforts, a Water-Business nexus is recognizable in Arizona. SanTan Brewing company has collaborated with the NFF initiating the reforestation campaign, "From Tap to the Top." According to the Water Research Foundation (2013), wildfires have detrimental impacts on water supply infrastructure and the provision of drinking water (p.56).

Energy and forests are also tightly intertwined in Arizona. The resilience of forests affects the security of energy systems. Aside from water as a cooling resource for thermoelectric power plants, wildfires in forests occasionally devastate electricity grids and other energy facilities such as substations, while causing power outages in communities (LaMaster, 2018). In this context, the Arizona Corporation Commission (ACC) proposed the promotion of biomass energy in Arizona's Energy Modernization Plan (Tobin, 2018). In this plan, for "the benefit of Arizona citizens and the health of Arizona's forests," the ACC proposes to regulate electricity utilities, which supply more than 100,000 MWh electricity to consumers, to use 60 MW of nameplate capacity biomass made up of "high-risk fuel" by December 31, 2021 while aiming at the completion of thinning one million acres of forests in 20 years.

Moreover, a complex threat is emerging in the pathological combination of chronic droughts and the engineering resilience perspective and its bouncing back to a steady state of 'thickness.' This pathological combination has jeopardized urban resilience intensifies wildfire risks in Arizona and the United States. Small and large wildfires have caused turbid water resources and communication/electricity outages coupled with monsoon seasons. For instance, the Schultz wildfire, ignited by an abandoned campfire on July 20th, 2010, manifested the complicated interdependence of water-energy-forests in Arizona. This fire destroyed a total of 15,051 acres in 10 days. The U.S. Forest Service Burned Area Emergency Response (BAER) team assessed potential risks after the wildfire to mitigate the fire impacts. After the BAER team assessed eleven basins within the burned area, five basins (4,5,7,9 and 10) were designated as basins of concern due to the burn severity, and the steepness of slopes in the devastated areas (US Forest Service, 2010; Koestner et al., 2011).

Aside from the destroyed forest areas, the Schultz fire caused a significant water quality problem early in the Monsoon season. The precipitation amounts at the ALERT rain gauges was around 1.6 inches, and a very high peak 10-minute intensity was 0.98 inches. That gave rise to a flood in the burned area. In addition, on August 16th, there was another high-intensity rainstorm and 10-minute intensity of 0.59 inches rain (US Forest Service, 2010). Due to the intense precipitation, a second flood swept the debris and ashes into the nearby reservoirs, which are dammed by SRP. Sediments, fire retardants, ashes, and burned organic matter all changed the water chemistry, turbidity, and the nitrate and organic carbon concentration. According to Combrink et al. (2013), flooding after the 2010 Schultz Fire caused millions of dollars in damages to downstream. According to the City of Flagstaff (2010), the cost of flood mitigation is approximately 50,000,000 dollars, which is much five times more than 10,000,000 dollars spent on fire response.

In 2012, the Sierra Nevada Conservancy, the Nature Conservancy, and the U.S. Forest Service modeled the factors that affected wildfire damage and found that the implementation of fuel reduction (forest treatment) can benefit the infrastructure resilience of the Mokelumne watershed. In the modeling, the fuel treatment resulted in considerable cost reduction totaling 2,600,000 dollars, including 1,600,000 dollars worth of transmission line protection and 1,000,000 dollars in avoiding sediment damage to water supply systems (Buckley et al., 2014).

9.3 Institutional Transformation for Forest Management in Arizona

Section 9.3 will investigate how the awareness and anticipation of risks of wildfires are incorporated into the forest management and thinning projects in Arizona. In the following sections, resilience processes will be vetted through the knowledge systems approach.

9.3.1 *Sensing* the fallacy of fire control

Sensing is a process in which the increase of wildfires is taken up to the decision makers as the warning signals of boundaries breaching. Sensing abnormalities in the system patterns are particularly significant as an indication of the necessity of new "patterned regularities" (Crawford & Ostrom, 1995). Resilience work can only be possible with sensing boundary breaches.

Despite a long history of fire extinguishment strategies, policymakers recognized that the efficacy of engineering assessment and extinguishment control had not been successful for fire-fighting (Agee, 1993; US Forest Service, 1996). One of the designated culprits was the poor management of ecological infrastructures, forests (i.e., the simplistic engineering approaches to forests). Until the 1970s, federal land managers, except Harold Weaver, who highlighted the use of prescribed fires, were most inclined toward the efficient scientific control of fires, and thus the detachment of fire-forest interdependencies without anticipating *unintended consequences* (Pyne, 1982; Arno, 1996a). Since the USDA Forest Service's founder, Pinchot left in 1910, and the organization has neglected the traditional knowledge of positive effects of wildfires on wildland forests preserved by Native Americans and other ecologists including Pinchot for decades. Pinchot argued for "the natural role of fire," but the "creative action of forest fires" has never been appreciated by federal-level organizations including the USDA Forest Service (Arno, 1996a). Consistent suppressions have typically resulted in more intense wildfires.

Meanwhile, in the 1970s, the increasing numbers of wildfires were evident (US Forest Service, 1996). Coupled with this recognition, the surge of wildfire acreage in western states (Arno, 1996a), a Report by Starker Leopold and others (1963) proposed the management transition to the federal agencies from a “fire control” scheme into “fire management” in 1970s (Lotan, 1979; Parsons & Botti, 1996; Arno, 1996a). Based on this advising, the National Park Service implemented the first prescribed burning in 1968 (Parsons & Wagtendonk, 1996). Then, forest managers began to understand the importance of prescribed fires in forest restoration processes and the negative results of engineered fire suppressions (Parsons & Botti, 1996). The Fire in Multiple-Use Management Research, Development and Applications (RD & A) Program (the USDA Forest Service) advised forest managers to understand the role of fire in the health of ecosystems, institutionalize this new fire scheme into management practices, and recognize the risks of linear suppressions (Loutan, 1979; Teensma, 1996).

Finally, in 1995, the US National Forest Service held a conference session, “The Use of Fires in Forest Restoration” on the direction of forest restoration at the Society for Ecological Restoration at the University of Washington. In Arizona, the ecological resource of the Ponderosa Pine forests was burned by severe wildfires in the 1990s. In 1997, the Greater Flagstaff Forest Partnership (GFFP), with the Coconino National Forest of the US Forest Service, Northern Arizona University, and the Wildland Fire Management division of the city of Flagstaff, were established to *manage* fires in Ponderosa Pine forests (O’Grady, Camey, & Vogel, 2016). William Covington, Director of Ecology Restoration Institute at Northern Arizona University (NAU), has focused on healthy forest management and the role of fires in forest resilience since the 1970s. The Ecology Restoration Institute at NAU has significantly contributed to the Four Forest Restoration Initiative (4FRI), which is a project that aims at restoring 2.4 million acres forests in Northern Arizona since 2012. The increasing wildfires became not just an issue in Arizona but also in the broader context, the United States.

9.3.2 *Anticipating* more fires within forest boundaries

"Anticipatory Governance," (Barben et al., 2008; Guston, 2014) collectively practicing imaginaries and building consensus for future uncertainties, which are different from foresight or prediction, is an essential step in resilience knowledge processes. Anticipating is a procedure that relates past observed data and monitoring warning signals of future systems. In resilience engineering, anticipation means developing future strategies in preparation for "possible crisis and disasters." Anticipation does not need to be based on quantified assessments, but rather the qualitative enhancement of sensing (Park et al., 2013). The way Hollnagel (2011) and Park et al. (2013) term anticipation coordinates with the definition of anticipatory governance which means "a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible" (Guston, 2008; Barben et al., 2008; Guston, 2014). Anticipation in Arizona for forest resilience can be characterized by preparatory planning, engagement efforts, and the integration of stakeholders' **epistemologies** in preparation for future disruptions such as increasing wildfires (Barben et al., 2008; Guston, 2014).

Increasing wildfires signaled the malfunction of forest systems. Moreover, the correlation between high temperatures and wildfires ignited epistemological anticipation.

There is a clear correlation between the increase of temperature and wildfires in the Western United States. As the mean temperature in March through August in the West goes up, the annual frequency of forest wildfires, which burn over 400 ha, increases. For instance, in 1970, the mean temperature was approximately 13.5, and the number of wildfires was 30. However, in 2003, the number increased to approximately 100 as the mean temperature reached 15 (Westerling, 2008). Currently, wildfires (> 10,000 acres) on U.S. Forest Service Land are about seven times more than 40 years ago (Climate Central, 2012).

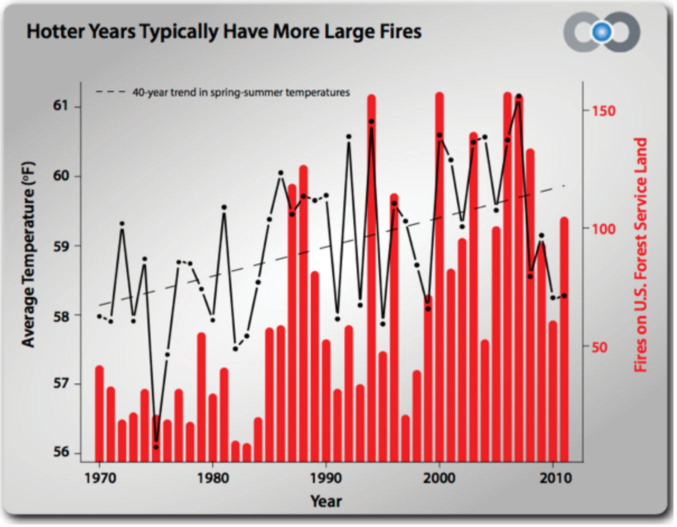

Figure 35. The average temperature and fires (source: Climate Central, 2012)

In particular, in the West, the fire season has increased by 78 days since the mid-1980s (Westerling et al. 2006). Tinning treatment and prescribed burning would mitigate CO_2 emissions by burning small diameter trees and shrubs and reducing fuel supporting fire (Finkral and Evans 2008; Wiedinmyer and Hurteau 2010). The goal of fuel management is to change wildfire behavior through changes in the fuel complex (Finney, 2001; Raymond & Peterson, 2005).

Concerns and anticipation about the increase of temperatures as well as wildfires forced the involvement of federal departments. At the federal level, severe wildfires—6.7 million acres were burned—in 2000 pushed the Clinton Administration toward a new institution, the *National Fire Plan* for fire prevention and funding proposed by Interior Secretary Bruce Babbitt and Agriculture Secretary Dan Glickman. This new plan augmented the budget for firefighting and prevention from 1.1 billion dollars to 1.8 billion dollars for FY 2001. This new plan included fuel treatment (hazardous fuels treatment) (thinning and prescribed burning). The western states' governors supported this new plan (Pinchot Institute for Conservation, 2002; Janofsky, 2000).

In Arizona, the Forest Healthy Council and the Forest Health Oversight Council was created by Governor Janet Napolitano with the recognition of increasing frequency and intensity of unnatural wildfires caused by human land use, fire suppression, and climate change (Executive Order, 2003-16). The Forest Healthy Council was focused on the development of scientific information and policy recommendations to advise the Governor's administration in addressing forest health, unnaturally severe fires, and community protection. This assessment of forest health discovered that the collaboration between multiple stakeholders and proactive actions are essential to restoring the resilience and health of Arizona's forests with respect to sustainable water supply in Arizona. In May 2006, a workshop was held in Flagstaff, and with input from a wide array of stakeholders, a draft for advising was made. In May 2007, six public meetings were held in different locations. Along with these investigative activities, the council proposed final advisory points in the document, *Statewide Strategy for Restoring Arizona's Forests* for the Governor on June 21st, 2007 (Governor's Forest Health Council, 2007).

In a recent report, *Wildfire Hazard Quantification and Effects on the Infrastructures* (U.S. Forest Service, 2015), infrastructures such water and energy infrastructures were identified as a social resource that would be damaged by wildfires. Based on the simulation and survey results, experts expected infrastructures such as transmission lines, communication facilities, mineral operations, Oil and Gas Storage Tanks & Pipelines would be significantly affected by 12 feet high wildfires. According to "Mokelumne Watershed Avoided Cost Analysis (2014)," forest treatment impacted fire suppression and rehabilitation costs, with treatments, avoided costs vary from 35 to 43.3 million dollars (Buckley et al., 2014). Recent modeling of wildfire risks and electricity resilience in California reveals that the transmission lines in the state will be increasingly exposed to wildfire risks across the state (Sathaye et al. 2012).

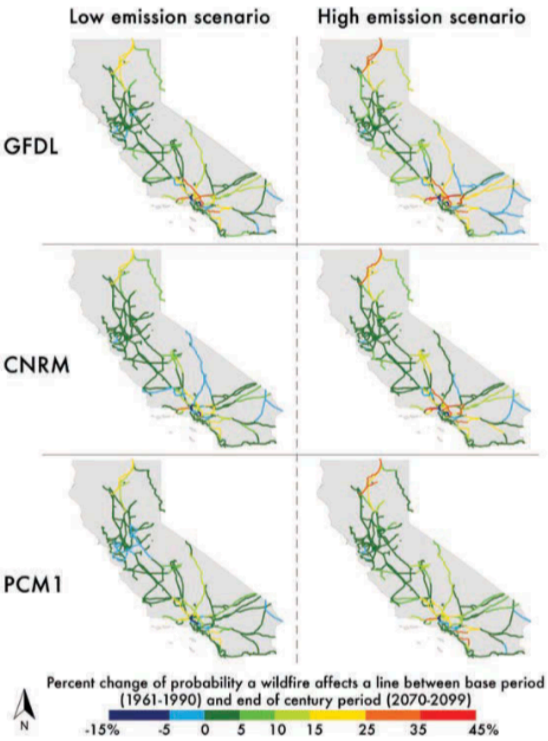

Figure 36. Projected wildfires and the increase of grid failure probability (source: Sathaye et al. 2012)

9.3.3 *Adapting* 'thick forests' to climate change: fire control to fire management across boundaries

In the 1990s, an institutionalization of fire management for ecosystems was ordered by the Federal Wildland Fire Management Policy and Program Review (Teensma, 1996). Since then, Thinning treatment and prescriptive fires were proposed by many scientists, land managers, and restoration practitioners. According to Fule et al. (2001), potential fire behavior can be reduced by following forest restoration treatments. Using "tree thinning, prescribed burning, and/ or other fuel reduction methods," new regime shifts such as new institutional practices for frequent, low-intensity fires, and sparse vegetation landscapes to forest management were recommended in the 2000s (Fule, McHugh, Heinlein, and Covington, 2001). According to Fule et al. (2001), "thinning treatments substantially reduced fire behavior under the same environmental circumstances." Also, it was revealed that some economic benefits from forest product removal could be gained through thinning (Larson and Mirth, 1998).

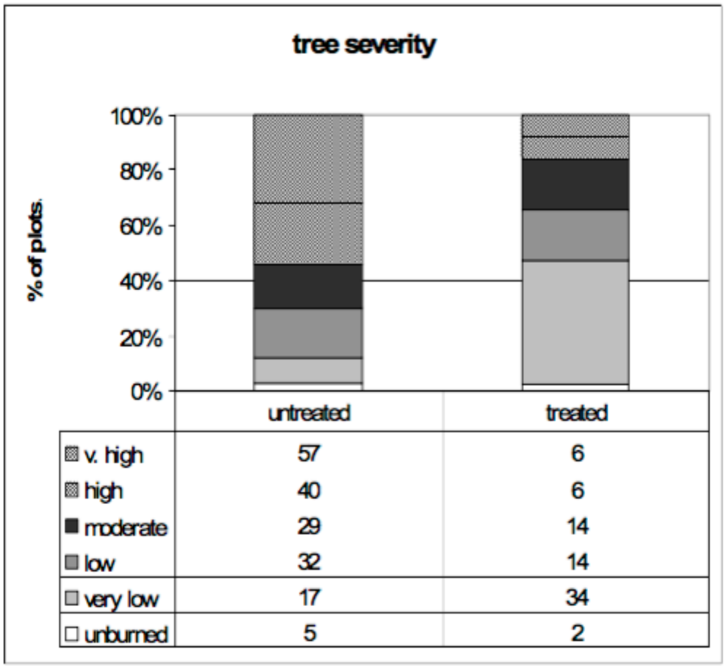

Figure 37. Treatment effects and the damage severity (source: Fule, McHugh, Heinlein, and Convington, 2001)

In **Fig. 37**, the correlation between fire severity and forest density is clear. The fire behavior assessment team assessed this correlation after the Antelope Complex Wheeler Fire. Wildfires severely burned the treated areas, but the treatment of forest reduced fire behavior and lessened soil impacts. It was observed that the severe and intense crown fire (high heat) was transitioned and contained into small surface fires in the pre-treated areas. Fire suppression practices have changed the dynamics of fire in ponderosa pine forests across the southwest (Fites et al., 2007; North et al. 2009).

Restoration treatments mitigate fire behavior and effects while providing multiple additional benefits and healthier ecosystems (Covington et al. 2001; Omi and Martinson, 2002; Fulé et al. 2001; Fiedler and Keegan 2003; Triepke et al. 2011). Pre-treatments and prescribed wildfires changed wildfires behavior in the treated areas. Pre-treated/burned areas are more likely to make surface fires producing effects beneficial to the ecosystems. Surface fires are easier to manage than crown fires (Westerling et al., 2006, p. 271). Thinning treatments and prescribed burning are expected to mitigate CO2 emissions from wildfires as well. For instance, the San Juan Fire, 2014 proved the efficacy of treatments. The San Juan Fire harmed the untreated forest area on the right side (7,000 acres) of the road, but the left side, the treated forest, was not affected by the fire (Thorpe, B. 2015).

Figure 38. Treated vs. Untreated (source: Thorpe, B. 2015; Photo: Bob Thorpe)

In the meantime, the frequency of wildfires has worsened, and fire seasons have become longer. Wildfires of larger than 10,000 acres are about seven times more now than 40 years ago on U.S. Forest Service Land (Climate Central, 2012). Responding to these threats, *Review and Update of the 1995 Federal Wildland Fire Policy* was done in 2001. *Interagency Strategy for the Implementation of Federal Wildland Fire Management Policy* was established in 2003. In 2009, USDA and USDOI stated and integrated the management of ‘fire, as a critical natural process’ into an institution for the “plans and activities” of land and resource management, which is *Guidance for Implementation of Federal Wildland Fire Management Policy*. In turn, guidance for fire management activities was also incorporated into the Forest Service Manual 5100 for the USDA Forest Service.

However, this transition from “thickening” to “thinking” has been struggling with and confronted by other administrative ‘**uncertainties’** such as “funding for prescribed burning and silviculture” and “the smoke emissions produced by prescribed burning” which impose legal burdens upon forest managers (Arno, 1996a; 1996b). Legal, operational, and financial constraints were the main reason of underprovision of thinning practices. Not only legal protection of wilderness, operational limitations due to slope steepness, and financial budget limits impeded prescribed burning or “managed wildfires”, but also these proactive practices rely on several crucial conditions such as moderate weather, smoke controls, and managing fire intensity which is out of human control (North et al., 2015). For instance, in 1994, the suppression of “frequent low-intensity fires” devastated ponderosa pine forest areas in the West (Arno, 1996b).

Also, with respect to ‘**value**’ discrepancies, there have been consistent debates between the U.S. Forest Service and environmental advocacy groups. In Arizona, the issue of the endangered Mexican spotted owl was one case. In 1993, the Co-founder of the Center for Biological Diversity, Robin Silver (emergency physician) pressed the U.S. Fish and Wildlife Service to protect the Mexican spotted owl (MSO) as an endangered species under the Endangered Species Act. In 1994, Silver asked U.S. Fish and Wildfire to designate a habitat area for the MSO by litigation. Federal Judge Carl Muecke issued an injunction preventing the cutting of certain types of forests in Arizona, New Mexico, and the other Southwestern region in August 1995. In December 1996, the order was lifted. Through this period, the economy of the timber industry in Arizona collapsed. After the injunction was eliminated, the filing of other lawsuits by non-profit environment groups halted the thinning projects in Arizona. In 1996, 2000, 2003, and 2012, the center for biological diversity group sued the U.S. Forest Service and required to protect the habitat of MSO. For instance, in the case of *Forest Guardians v. Thomas (October 1996)*, the Center for Biological Diversity and the Forest Guardians (New Mexico) challenged the new guidelines for the MSO. The two groups asked the Court for an injunction against the older forest thinning plans. In December 1997, the 9the U.S. Circuit Court of Appeals rejected these appeals. In the case of *Center for Biological Diversity v. Bosworth (May 2000)*, the Center for Biological Diversity filed a lawsuit in arguing that the U.S. Forest Service had not abided by the procedural rules to develop the Baca Ecosystem Management Area plan, including commercial timber cutting. In the case of *Forest Conservation Council v. U.S. Forest Service* (January 2003), after the Rodeo-Chediski fire, the U.S. Forest Service developed a plan to sell the dead trees resulting from the fire. The council sued the U.S. Forest Service while claiming the violation of federal laws regulating the procedures (e.g., environmental assessment) (Cowan, 2015; Blois, 2017; The Associated Press, 2012)

9.3.4 *Learning* from 4FRI projects

The applications and tests of new knowledge content and structures complete the knowledge learning process of resilience. The usefulness of adaptive strategies (e.g., low-intensity fires and thinning) are finally verified through these learning processes. Verified lessons are learned and typically incorporated into **knowledge structures** such as practices, standards, rules, and constitutions for sensing, anticipating future patterns, and suggesting alternatives when facing new normals. New **knowledge content and structures** ultimately accomplish **knowledge unlearning**.

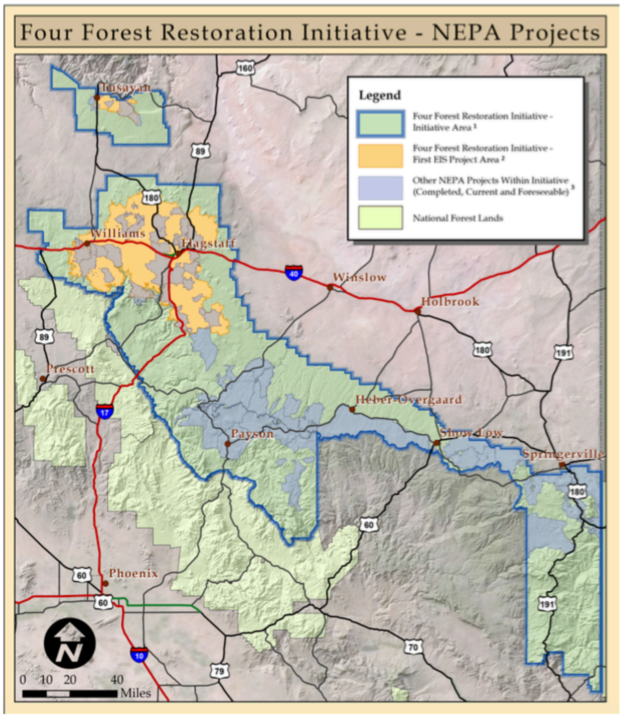

Figure 39. Four Forest Restoration Initiative Area

(source: 4FRI Webpage)

In Arizona, as a learning process, 4FRI is a collaborative effort to restore forest ecosystems of four national forests—Coconino, Kaibab, Apache-Sitgreaves, and Tonto along the Mogollon Rim in northern Arizona. Thinning 50,000 acres of forest annually for 20 years across the Tonto, Coconino, Apache-Sitgreaves, and Kaibab national forests are the project goal of 4FRI. These four forests are overgrown with young and unhealthy trees that contribute to the threat of unnaturally-severe wildfires. The goal of the 4FRI is to restore forests that allow low-intensity surface fires. Specifically, the 4FRI's purposes are four-fold: i) experimenting restoration treatment across 2.4 million acres of ponderosa pine forest; ii) for restoration, implementing the increased use of prescribed fire and management of natural fires; iii) supporting and promoting new business models for timber industries to cover the cost of restoration by selling removed trees and pallets; iv) establishing science-based and socially acceptable agreements promoting the implementation of long-term, landscape restoration (4FRI Webpage).

The Four Forest Restoration Initiative (4FRI) started in 2011. For five years, they used both methods to restore and protect forests from wildfires. For the assessment of 4FRI, the impact assessment of environmental and social effects (EIS, Environmental Impact Statement) of this project was approved on April 17th, 2015 according to National Environmental Policy Act (NEPA). The first EIS assessed about 750,000 acres of ponderosa pine vegetation on the Coconino and Kaibab forests. 4FRI is an experimental learning process of resilience knowledge systems to review and evaluate the efficacy of institutional transformations in managing forests: both thinning treatments and prescribed burning.

9.4 Conclusion

The implications of each chapter from Chapter 2 to Chapter 4 are as follows: the sociotechnical systems approach to infrastructures (Chapter 2), the new definition of infrastructure resilience (Chapter 3), and the respective resilience implementations of different institutions for infrastructures (Chapter 4). The sociotechnical perspective was applied to Chapter 5 to explain the adaptive, institutional work for the long-term management of Hoover Dam. Chapter 6 analyzed the institutional threads managing water and energy infrastructures and the resilience work (operational, regulatory, and transformational work) of these threads over time. Further, Chapter 7 investigated the interdependencies of resilience work which focuses on how institutional changes in water systems institutionally affect the management of electricity supply infrastructures in Arizona. Chapter 8 employed and tested the efficacy of the 'risk innovation' framework as a tool to analyze threats from water shortage issues on different value constituencies for long-term adaptations and transformations in a vast landscape of infrastructures.

Chapter 9 argues that the resilience of water and energy infrastructures are inexplicably coupled with the resilience of forest management in Arizona. Transformation processeses in forest management in Arizona illustrate how an institutional transition from fire control to fire management affects urban resilience. This resilience transition can be better understood from the perspective of knowledge systems approach and knowledge components. The resilience processes of sensing, anticipating, adapting, and learning in Chapter 9 elaborate the processes of resilience transition in forest management. The descriptive work on the changes of forest management in Arizona accentuates the indispensable work of institutions to the transformational changes of socio-eco-technical infrastructures for resilience.

CHAPTER 10

CONCLUSION

10.1 Summary of Findings

- Infrastructure is not just technology. It also includes social arrangements (e.g., the organizations and workforces that manage technology and the use of technology by users to create valuable services) and various forms of labor and work to imagine, design, build, operate, repair, adapt, and transform technologies over time. This view should be a critical point in managing for infrastructure resilience, which requires maintaining and/or recovering both the physical performance/capabilities of technologies and the social arrangements and forms of work necessary to support those.

- The resilience of infrastructures is, therefore, not simply a static feature of the technical or engineering design of a physical (or cyberphysical system) but rather a dynamic accomplishment or an outcome of institutional resilience work. This feature of infrastructure dynamics necessitates a transition from conventional engineering approaches toward alternative **ideas** and **actions** that emphasize whether or not institutions are doing the work necessary to create stability (in the short-term), in order to maintain infrastructure services); adaptability (in the medium-term), in order to respond to incremental changes in infrastructure contexts and environments; and transformability (in the long-term), in order to respond to changing societal and economic needs and values.

- In terms of new resilience **ideas**, understanding and improving infrastructure resilience requires consideration and analyses of the social and institutional work required. This requires, in turn, improved understanding of the institutional governance of interdependent infrastructures across multiple scales, the uncertainties institutions confront, and the differences in organizational objectives and resilience frameworks associated with operational, regulatory, and constitutional institutions.

- With respect to resilience **actions**, infrastructure institutions need to better understand and execute their resilience work, so that infrastructure can be made, as appropriate, stable, adaptable, and transformable over time. In other words, enhancing the resilience work of institutions and the knowledge and operational capacities of institutions to carry it out should be a focal point of resilience policy and investments in improved resilience.

- This research provides theoretical insights and empirical analyses of institutional approaches for enhancing infrastructure resilience. While resilience analyses often highlight the role of institutions in managing post-disaster responses, this analysis focuses on the role of institutions prior to disasters in creating the conditions for resilience by properly operating, regulating, and constituting infrastructures through complex, institutional work and the management of interdependencies in social systems. Mapping, cataloging, and implementing the resilience work of institutions has the potential to help avoid chronic infrastructure inefficiencies or acute failures and thus to improving the resilience of infrastructures over time.

10.2 Research Implications

The case studies in this research attest to the fact that improving infrastructure resilience requires explicit understanding of institutional arrangements in response to social changes and biophysical challenges such as climate change. The maladaptation of institutions and misinformation can lead to resilience failures of infrastructures. The current institutional mismatches will manifest in infrastructure failures in the future. Furthermore, recurrent institutions and resilience failures give rise to low level trust in public politics which in turn diminishes political leadership in the long term (Vinck et al. 2019).

The optimal alignment of institutional threads (e.g., vertical, lateral, and longitudinal threads) for infrastructures can be achieved via rigorous analyses on infrastructures with diverse institutional matrices such as risk assessment, life-cycle assessments, cost-benefit analyses, environmental impact assessments, social impact assessments, customer satisfaction indices, inclusive civic participation, risk innovation, and resilience politics. This research can help to design more resilient infrastructures wherein well-aligned metrices and approaches play out to construct, operate, maintain, reconfigure, and redesign infrastructures (McDaniel et al., 2013).

Infrastructure is a dynamic sociotechnical system. Infrastructure is not a static nor a physically independent system. Infrastructure by definition a mediation—a "quasi-object" (Latour 1991)—between society and technoscience. The management of infrastructures for resilience requires the optimal alignment of both the engineering and institutional aspects of water and energy systems (Finger et al., 2005). Thus, to improve the resilience of our infrastructures to climate change, we will first have to improve the institutional 'landscape, regimes, and niches (Geels, 2005).' How do institutions improve resilience? How do institutions detract from resilience? These questions are critical to infrastructure resilience. This sociotechnical awareness helps to understand how to prepare institutions for future internal or external disruptions to infrastructure.

Most importantly, the institutional matrix should take into consideration the dynamics of balancing of institutional management to render infrastructures stable yet flexible in a nuanced way. Different functions of institutions such as operational, regulatory, and constitutional institutions stabilize, regulate, and transform institutional arrangements for infrastructures with different organizational structures, for different goals, and at different temporal and geospatial scales. Different (e.g., operational, regulatory, and constitutional) institutions fit distinctive resilience frameworks such as engineering resilience, resilience engineering, and general resilience.

Moreover, infrastructural interdependence is comprised of not only physical but also institutional linkages. Vulnerabilities run through direct or indirect interdependence networks of infrastructures (Eakin et al., 2018), and thus interdependence grids transport vulnerabilities and trade-offs through institutional conduits. Thus, climate stressors and other infrastructure risks run through these settings of institutional matrix of infrastructures while disrupting past, present, and future institutional arrangements. Institutional changes in one part (e.g., water systems) give rise to impacts on the operation and management of counterparts (e.g., energy systems). For instance, infrastructure resilience management should incorporate water governance changes to power plants of APS and conflicting regulations (e.g., water conservation and air quality) on circulation and vaporization practices of cooling water in Palo Verde plant's stacks. Given institutional interdependence, a linear resilience concept from engineering reductionism does not fit in dealing with infrastructural management. Rather, infrastructure resilience challenges typically accompany political and value questions for our sociotechnical society (see Maynard (2015) on *risk innovation*).

The significance of institutions for infrastructures is also evident in socio-eco-technical networks of water-energy-forest systems in Arizona. These lessons learned from the liaison studies between institutions and infrastructure resilience in this research provide a couple of suggestions in making public policies in the section 10.3.

10.3 Policy Suggestions

Policymakers should be wary of three institutional aspects in making policies regarding infrastructure resilience: outdated data, social complexity such as institutional interdependencies, and trade-offs. In particular, modeling amalgamated with static data

(Katz, 2010), unclear hierarchies and overlapping jurisdictions of regulatory policies, and trade-offs convoluted with organizational proliferation (Tyler et al., 2016; Eakin et al., 2016) in transformative processes can result in worsening infrastructure vulnerabilities rather than enhancing resilience.

In particular, the first and most significant challenge to sociotechnical adaptation is incorporating climate change awareness to *upgrade modeling and institutions* that manage infrastructures (Sampson, Quay, & White, 2016; Doherty, M., Klima, K. & Hellmann, J., 2016). Otherwise, the outdated institutions rather detract from infrastructure resilience. Outdated data conditions, such as precipitation patterns, considered “normal” in the 20th century no longer work for infrastructures in the next decades (Milly et al., 2008; Katz, 2010) Weather extremes and unanticipated variability from climate change are challenging existing institutional systems for infrastructure. The climate resilience of infrastructure depends on whether institutions successfully update the best available information on climate change trends and coherently improve their protocols, regulations, and constitutions for modeling, upgrading, replacing, and transforming infrastructure.

The second institutional point for infrastructure resilience is *institutional interdependencies* of sociotechnical contexts. For instance, new community norms, such as a commitment to reduce carbon emissions, can force rapid and unanticipated changes to the energy infrastructure. Due to the tight water-energy nexus, new CO_2 emission regulations on electric utilities can significantly affect water systems and water prices.

Likewise, changes in the availability or temperature of surface water due to climate change ramify onto the electric system (e.g., gas-fired turbine transition). Preparing for climatic challenges requires an integrated perspective on the *interdependence* of these two systems.

Lastly, *trade-offs* challenge comes from the intersection of the first (institutionalization) and the second (interdependence) stated above. The physical and institutional complexity of infrastructure can exacerbate vulnerabilities when coupled with long-term or short-term climate stressors. The landscape of coupled water and energy systems in Arizona consists of a complex network of myriad organizations–15 energy utilities and 54 water utilities registered at the AZ Corporation Commission as of 2017. If we include private providers not registered with the ACC, the number of water providers would be over 100 (Larson et al. 2013, p.64). The collective action of a system cannot be reduced to "aggregations or direct consequences of individuals' attributes or motives" (March and Olsen, 1984). Thus, this institutional complexity requires coordination and cooperative negotiation on diverse trade-offs for updating institutions (Janssen & Anderies, 2007; Leichenko, 2011; Tyler et al., 2016; Eakin et al., 2016).

10.4 Future Research

For possible future work, broader and more diverse political and regulatory contexts can be explored in line with the sociotechnical systems approach to urban resilience and interdependent systems. These contexts can include the variations of sociotechnical concepts, the sociotechnical contexts of urban resilience conflicts at local and global scales, climate extremes to urban resilience and trade-offs, resilience and equity issues, and regulatory failures in energy disasters in relation to urban resilience.

First, one of future research can be focused on how climate change draws upon multiple variations of resilience concepts, represented in laws and regulations associated with the climate adaptation of infrastructures in global contexts. The concept of resilience has been interpreted by diverse global communities and applied to governmental policies in various forms of climate strategies (e.g., redundancy, adaptiveness, and flexibility). Second, another possible project can be examining how the epistemological strategies of urban resilience at the global scale can disrupt pre-existing trade-off settings at a regional scale. This research will be focused on innate trade-off challenges (e.g., gentrification versus green infrastructure for safe-to-fail strategies, food industry versus water-efficient products, and so forth) to infrastructures concerned with regional adaptations in global communities in response to climate change. Third, one possibility may include relating a new theoretical interpretation of resilience for a balanced, empirical approach to the political geography issues of *resilience equity* while elaborating utilities and shortcomings of resilience concepts in regional planning.

This research points to possible spaces for improving resilience assessments and politics. By denying either linear engineering or process-centric resilience approach, the congruence and optimization of establishing and implementing resilience policies can be pursued with the resilience framework of this research. On a small scale, operational institutions fit in engineering resilience, but general resilience is more appropriate in the long-term and on a large scale. Yet, the boundaries of the respective small, medium, and large scales are not clear. In some cases, individual transformation on a small scale is also possible. Furthermore, decision making to scale up or scale down is a more complex task. In a timely manner, how to categorize and work each resilience case into either stability or flexibility or even transformability-centric order is a more challenging question to policymakers. Who participates, in what ways, and to what effect in resilience boundary work? (Miller, 2017) To put boundaries, we first need to make clear boundaries to all constituencies. In this vein, resilience work and consideration of this research interrogate our democracy.

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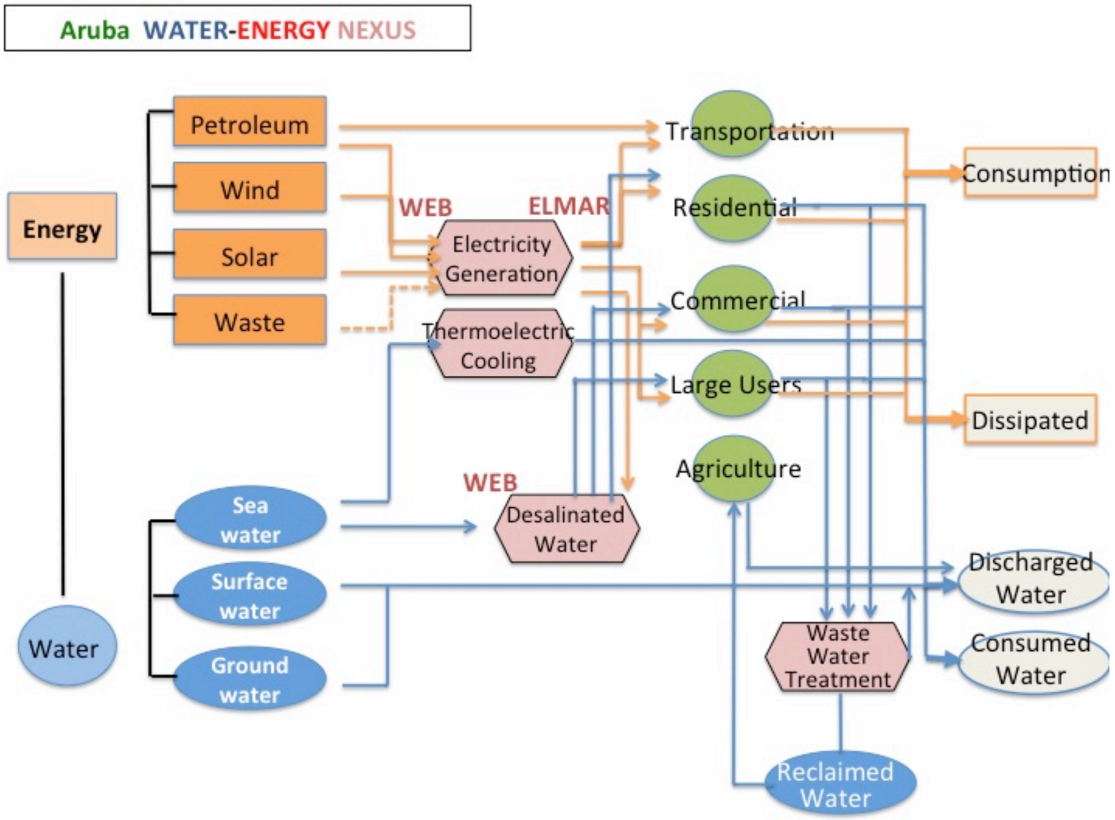
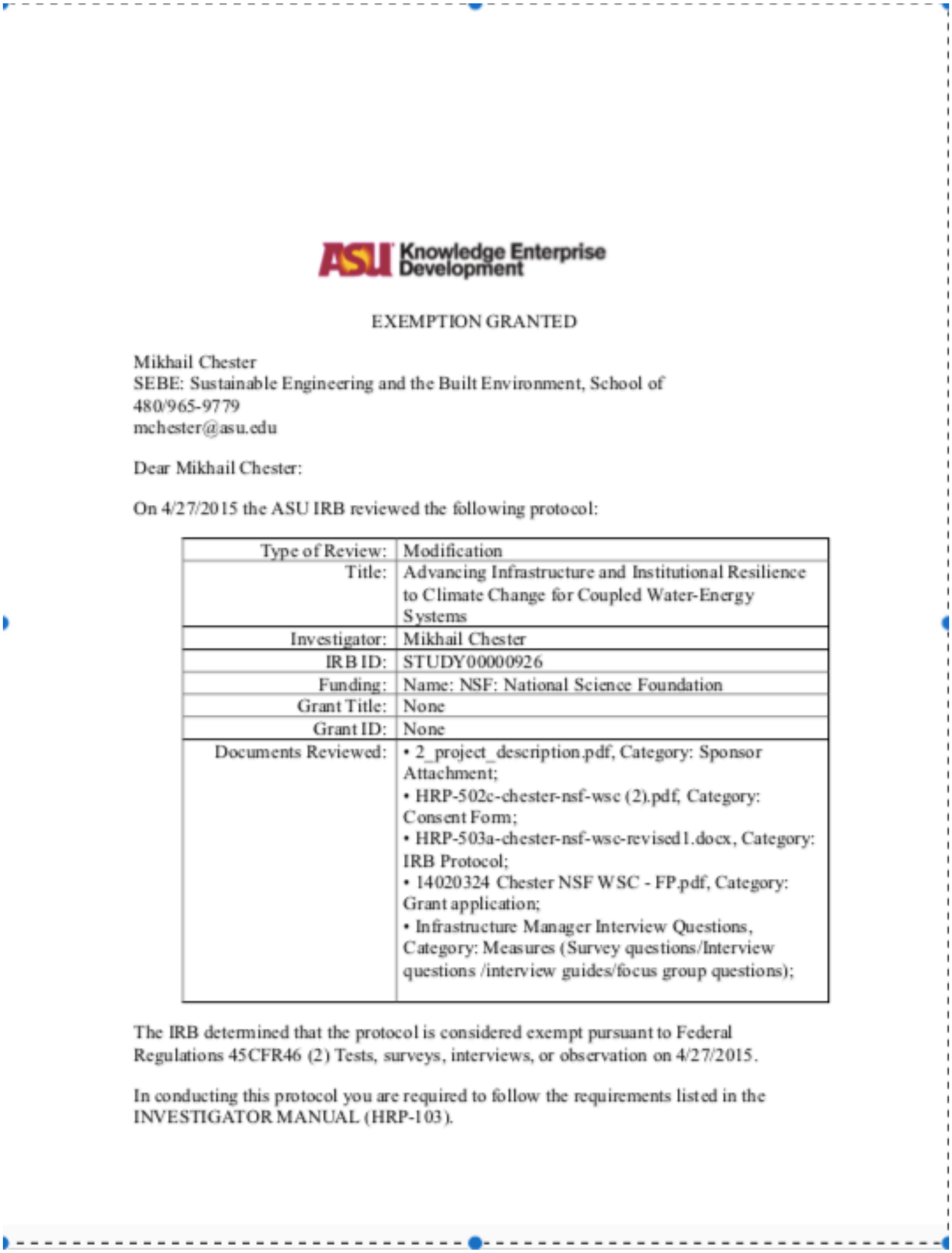
APPENDIX A

WATER AND ENERGY NEXUS IN ARUBA


Aruba WATER-ENERGY NEXUS
Energy
Petroleum
Wind
Solar
Waste
WEB
ELMAR
Electricity Generation
Thermoelectric Cooling
Transportation
Residential
Commercial
Large Users
Agriculture
Consumption
Dissipated
WEB
Desalinated Water
Water
Sea water
Surface water
Ground water
Waste Water Treatment
Reclaimed Water
Discharged Water
Consumed Water

APPENDIX B

IRB PERMISSION



ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Mikhail Chester
SEBE: Sustainable Engineering and the Built Environment, School of
480/965-9779
mchester@asu.edu

Dear Mikhail Chester:

On 4/27/2015 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Advancing Infrastructure and Institutional Resilience to Climate Change for Coupled Water-Energy Systems
Investigator:	Mikhail Chester
IRB ID:	STUDY00000926
Funding:	Name: NSF: National Science Foundation
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• 2_project_description.pdf, Category: Sponsor Attachment; • HRP-502c-chester-nsf-wsc (2).pdf, Category: Consent Form; • HRP-503a-chester-nsf-wsc-revised1.docx, Category: IRB Protocol; • 14020324 Chester NSF WSC - FP.pdf, Category: Grant application; • Infrastructure Manager Interview Questions, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 4/27/2015.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

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[1] According to US National Science and Technology Council, resilience is a capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures (US National Science and Technology Council).

[2] Southern California Edison had opposed to any government dam on the Colorado River. It wanted hydroelectric dams to be built by the private sector. However, Congress rejected that position, so Southern California Edison tried to ensure that government dams remained small. It did not want inexpensive publicly owned power to compete with its own power generation in the electricity market. In the late 1920s, after the US government confirmed again its intention to build a large hydropower dam on the Colorado River in the 1928 "Report of the Colorado River Board on the Boulder Dam Project," the company requested permission to be involved in power generation in the Colorado River Basin. After Congress also rejected this, it asked for the right to distribute the hydroelectricity from the dam. The company then lobbied Congress to allocate the states of Arizona and Nevada a larger share of the power from Boulder Dam, believing it would be able to buy that cheap power and distribute it at a profit in rapidly growing southern California. Donald Pisani, *Water and American Government: The Reclamation Bureau, National Water Policy, and the West, 1902-1935* (Berkeley, CA: University of California Press, 2002), 233-234; Paul L. Kleinsorge, *The Boulder Canyon Project* (Stanford, CA: Stanford University Press, 1941), 79.

[3] "… Applications should state the quantity of power desired and should contain a general statement concerning the purposes and place of use of the power covered by the application, with such other information as may be considered necessary. The early submission of applications is desirable in order that a decision may be reached concerning the allotment of the power to be made available by this development."

[4] Applicants applying for hydroelectricity from Hoover Dam

Applicant	Date of application	Horsepower	Load factor (%)	Millions of kWh	Remarks
State of Nevada	Sep. 8, 1929			1,200	
State of Utah	Oct. 1, 1929	50,000			
Metropolitan Water District	July 5, 1929	280,000	98	1,789	
Mohave County, Arizona	Sep. 28, 1929	100,000			

City of Los Angeles, California	July 5, 1929	[1]1,000,000	[1]55	3,600	
City of Burbank, California	Sep. 24, 1929	[1]6,800	[1]45	20	
City of San Bernardino, California	Oct. 21, 1929	10,000	[1]45	[1]29	
City of Pasadena, California	Sep. 24, 1929	24,500	45	72	
City of Glendale, California	Sep. 21, 1929	[1]17,000	[1]45	50	
City of Riverside, California	Oct. 24, 1929				Amounts not stated
City of Santa Ana, California	Sep. 30, 1929	10,000	[1]45	[1]29	
City of Newport Beach, California	Do.	10,000	[1]45	[1]29	
City of Beverly Hills, California	Oct. 30, 1929				Do.
Southern California Edison Co.	July 5, 1929	[1]850,000	[1]65	3,600	
Central Arizona Light & Power Co.	Oct 5, 1929				Do.
Los Angeles Gas & Electric Corporation	Sep. 24, 1929	73,000	[1]37	[1]177	Or 7.3% of California allocation
The Arizona Power Co.	Sep. 30, 1929	30,000	[1]50	[1]98	
Yuma Utilities Co.	Sep. 27, 1929	26,800	[1]45	[1]79	
Southern Sierras Power Co.	Do.	[1]72,600	[1]60	286	7.94% of all generated

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Public Utilities Consolidated Corporation	Sep. 28, 1929	134,000	[1]50	[1]394	
San Diego Consolidated Gas & Electric Corporation	Sep. 27, 1929				3.9% of California allocation
Katherine Midway Mining Co.	Sep. 12, 1929	5,000	[1]50	[1]16	
Consolidated Feldspar Corporation	Sep. 25, 1929	325	[1]50	[1]1	
J. T. Dobbins, Fredonia, Arizona	Sep. 10, 1929				Amounts not stated
United Verde Copper Co.	Sep. 23, 1929				Do.
Palo Verde Mesa & Chucawalla Valley Development Association	July 3, 1929	30,000	[1]50	[1]98	
City of Colton	Oct 21, 1929	3,000	45	9	

1 Quantities assumed from best data available.

[5] General regulations for lease of power VI (1) (a) One and sixty-three hundreds mills ($0.00163) per kilowatt-hour, for firm energy (The United States Department of the Interior. *The Hoover Dam power and water contracts,* 109.)

[6] There were 10 meetings of the Colorado River Commission for the Colorado River Compact. The first 7 meetings were held in Washington between January 26th and 30th in 1922. The members of commission were Norviel, W. (Arizona), McClure, W. (California), Carpenter, D. (Colorado), Serugham, J. (Nevada), Davis, S. jr. (New Mexico), Caldwell, R. (Utah), and Emerson, F. (Wyoming). (U.S. Department of the Interior, *The Hoover Dam Power and Water Contracts, 5*)

[7] This is according to the article II (b), (c), (d), (e), and (f) of Colorado River Compact. See the U.S. Bureau of Reclamation. *Updating The Hoover Dam Documents*, 4.

[8] For the total allocation for the state of California, there was final agreement among the Metropolitan Water District of Southern California, the Board of Water and Power

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Commissioners of the City of Los Angeles, and the Southern California Edison Co. on March 20th, 1930. The agreement is about the division of 64% hydroelectricity for the state of California. As a result of agreement, 36% was allocated to the Metropolitan Water District, 19% to the City of Los Angeles and other municipalities that have filed application, and 9% to the Southern California Edison Co. (U.S. Department of the Interior, *The Hoover Dam Power and Water Contracts,* 526)

[9] "H.R. 4349. Hoover Power Allocation Act" The House Republican Conference, accessed November 10, 2014, http://www.gop.gov/bill/h-r-4349-hoover-power-allocation-act/; "Introduction of the Arizona Power Authority" APA, accessed November 10, 2014, http://www.powerauthority.org/about-us/; "The Hoover Allocation Act – Fact Sheet." Colorado River Commission of Nevada accessed November 10, 2014, http://www.crchooverallocation.com/files/Hoover%20factsheet%20-%2020130801.pdf

[10] "Hoover Power Allocation Act" Senate Report 112-58 accessed November 10, 2014, http://www.gpo.gov/fdsys/pkg/CRPT-112srpt58/html/CRPT-112srpt58.htm

[11] "Conformed General Consolidated Power Marketing Criteria or Regulations for Boulder City Area Projects (49 FR 50582)." Western Area Power Administration, Department of Energy accessed November 10, 2014, http://www.wapa.gov/DSW/pwrmkt/PDProj/RefMaterial/Cgcpmc.pdf

[12] "President Signs Hoover Dam Power Allocation Act." Lisa Lien-Mager, accessed November 10, 2014. http://www.acwa.com/news/federal-relations/president-signs-hoover-dam-power-allocation-act

[13] "Comments upon proposed post-2017 Boulder Canyon Project Marketing Criteria To Desert Southwest Regional Manager Western Area Power Administration," Arizona Power Authority accessed November 10, 2014, http://2017.powerauthority.org/wp-content/uploads/2013/01/POST-2017-BCP-Comments.pdf

[14] "Comments upon proposed post-2017 Boulder Canyon Project Marketing Criteria To Desert Southwest Regional Manager Western Area Power Administration," Arizona Power Authority accessed November 10, 2014, http://2017.powerauthority.org/wp-content/uploads/2013/01/POST-2017-BCP-Comments.pdf

[15] "Notice of Proposed Allocation. (Federal Register Vol. 79, No. 153)." WAPA, Department of Energy accessed November 10, 2014, http://www.gpo.gov/fdsys/pkg/FR-2014-08-08/pdf/2014-18797.pdf

[16] "Notice of Proposed Allocation. (Federal Register Vol. 79, No. 153)." WAPA, Department of Energy accessed November 10, 2014, http://www.gpo.gov/fdsys/pkg/FR-2014-08-08/pdf/2014-18797.pdf

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[17] Service standard includes standards for voltage, frequency, and other technical requirements, distribution service

[18] The initial allocation for CAP delivery was 1.49 MAF. However, 75,000 AF was calculated as system loss. (Arizona water settlement agreement between the United States of America and the State of Arizona (2007))

[19] Minute No. 319: “Interim international cooperative measures in the Colorado river basin through 2017 and extension of minute 318 cooperative measures to address the continued effects of the April 2010 earthquake in the Mexicali valley, Baja California”