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RESEARCH ARTICLE

Resilience of Irrigation Systems to Climate Variability and Change: A Review of the Adaptive Capacity of Philippine Irrigation Systems

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Abstract: Irrigation is a socio-technical infrastructure for food and water security programs of many developing countries, including the Philippines. Consequently, the government has been heavily investing in irrigation development to boost crop yield and to enlarge currently irrigated areas for many years now. However, the Philippine climate has been changing; and the climatic variations and change present potential threats to the resilience of the Philippine irrigation systems. The impacts of climate variability and change on the resiliency of irrigation infrastructures challenge the sustainability of the government's investments in food security programs. Climate change would alter the Philippine water cycle thus changing the temporal and geographical patterns of rainfall, evapotranspiration, runoff, and groundwater recharge. Extreme hydro-meteorological events have been occurring more frequently in the country today—strong typhoons with undocumented wind speed and with rainfall of unrecorded amount and intensity are being experienced more often now than before. These extreme events bring about risks to irrigated agriculture because of the uncertainty of either too much or too little water, or both. The aforementioned risks will infringe upon the planning, design, and construction processes of new irrigation systems, and upon the operation and maintenance of existing ones. The study applied systems dynamics approach to review and analyze factors that strengthen or weaken the resiliency of the Philippine irrigation systems to the impacts of climate variability and change. The intrinsic system resilience to stresses and episodic shocks of climate variability and change emerge from the interrelationship and feedback interaction between the elements and irrigation processes in an irrigation system. The current internal dynamics in most irrigation systems exposes its incapacity to serve fully its designed area. As a result, the overoptimistic technical and economic assumptions used in the planning and design phase imperiled the intrinsic resilience of existing irrigation systems to climate variability and change. Moreover, the degradation of physical infrastructures attributable to low maintenance level and inadequate rehabilitation works result in continuing inability of irrigation systems to serve the designed area with adequate water and weaken their intrinsic resilience. The social components of the system--the irrigation agency, and the farmer community in particular, are undertaking varied adaptation actions to increase and strengthen both the system's "soft" and "hard" resiliency.

Keywords: Philippine irrigation systems, socio-technical systems, systems dynamics, emergence, climate change, system resiliency, adaptive capacity

JEL Classifications: Q15, Q54, Q18, H43

An irrigation system frequently experiences and adapts to varied forms of disturbance to continue to perform its basic function, that is, to deliver water adequately to meet farmers' irrigation demand on time. Farmers interfere in an irrigation system's water control and distribution function when it fails to deliver adequate water supplies on time (Moya, 1979; Moya, 2014). They interfere in system's function to make up for deficiencies in system's water delivery performance. Nevertheless, irrigation *per se* is an adaptation to disturbance and shocks from climate change. It is a component of generic adaptation plan to climate change of agricultural systems in most countries in Asia and elsewhere around the world. The food and water security programs of the Philippine government include irrigation as an essential program component. As such, it is important to look into adaptation factors that contribute to the resiliency of irrigation systems to the Philippine climate variability and change to protect and sustain the massive investments in irrigation development. The Philippine climate has been changing (Amadore, 2005; PAGASA, 2011; Cinco *et al*, 2013; Cruz *et al*, 2017).

Irrigation infrastructure is a technology introduced into a socio-ecological system and described better as a complex socio-technical system (STS) (Huppert & Walker, 1989; Saravanan, 2008). Yu *et al* (2009) remarked that community irrigation systems are complex social-ecological (technical) systems with hard man-made infrastructure (water diversion and conveyance structures), soft human-made infrastructure (institutional arrangements and organization forms) and, natural infrastructure (watersheds and agricultural lands). The complex interaction and feedbacks between the irrigation processes, social component (people, irrigation agency personnel and farming communities, and other stakeholders) and the physical infrastructures (headworks, dams, conveyance and distribution canals, and water control structures and facilities), sustain the dynamics in an irrigation system in a given watershed[1] (Vincent, 1997; Fishbein & Haile, 2012; Yu *et al*, 2015). Infrastructure design can influence STS resilience and sustainability through collection action dynamics (Yu *et al*, 2015; Francis & Bekera, n.d.).

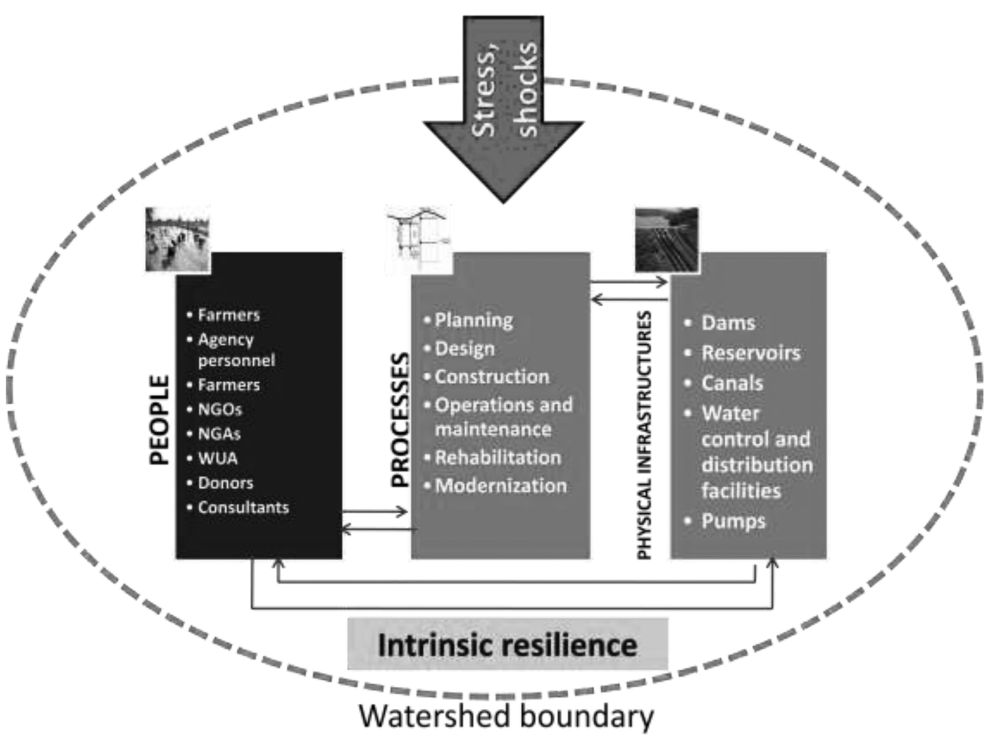

Figure 1. Irrigation is a socio-technical system introduced into and integrated with socio-ecological systems.

People follow processes of planning, design, construction, operation and maintenance, rehabilitation, and modernization in the control and use of the engineered (physical) infrastructures to secure adequate water supplies for farmers, water users' association, and other irrigation stakeholders (Figure 1). The physical infrastructure can mitigate the effects of recurrent disturbance thereby enhancing the resilience of the social subsystem. With this interaction, the suitability and flexibility of the physical infrastructures for delivering service to farmers will provide feedback to planners, designers, and operations and maintenance personnel. The feedbacks may require improvement or changes in processes and/or physical infrastructures to improve the functionality of the irrigation system. The dynamic interaction and feedback among irrigation components also influence the state of the socio-ecological system in which an irrigation system is located. It affects irrigation water supply availability and reliability and thus it influences system's adaptive capacity to hydrological anomalies due to climate variability and change. System resilience, particularly intrinsic resilience, emerges as a critical characteristic of complex dynamic systems (Walker *et al*, 2004; Fiksel, 2006; Folke *et al*, 2010; Williams, 2013) like irrigation socio-technical system to supply reliably adequate amount of irrigation water to farmers without deleterious effects on watershed resources. The dynamic interactions between system components and feedbacks processes in the watershed impinge upon irrigation system resilience to a certain degree. Nonetheless, the intrinsic resilience of most irrigation can be under threats from enduring stresses or shocks from episodic event, like drought or flood brought about by climate variability and change. At the same time, higher temperature will inflate crop irrigation demand because evapotranspiration will increase. Risks from extreme climate events destroy crops, drown livestock, and alter water supplies.

Too little or too much water, or both, are the direct potential impacts of climate variability and change on irrigation processes of planning, design, construction, and operation and maintenance of irrigation systems for sustained functionality. Functionality improves resilience, so it will be necessary to incorporate investments in resilience into the planning and design process of new irrigation systems or in the modernization of existing ones (FAO, 2007; Williams, 2013). Under projected climate variability and change, to stay resilient, irrigation systems should strengthen adaptive capacity to bear anticipated climate risks. The study centered on analysis and synthesis of intrinsic resilience by looking into elements of adaptive capacity and sensitivity to stresses and shocks from climate variability and change of Philippine irrigation systems.

Review Methodology

Given the foregoing, the traditional approach to study irrigation system by focusing separately on the social, infrastructural, and environmental components will limit the interpretation of findings by missing the important interactions and feedbacks between components and irrigation processes. Based on the systems thinking philosophy, system approach can reveal system resilience as a system property that emerges out of the complex web of interactions and feedbacks between components, and processes in irrigation systems (Wang *et al*, 2009) (Figure 2).

Resilience has numerous and varied definitions as there are many disciplinal areas and norms in ecology, engineering, hazard management, sociology, psychology, operations, and so forth (Holling, 1973; Folke *et al*, 2004; Bhamra & Burnard, 2011; Ruault,Vanderhaegen, & Luzeaux, 2012; Williams, 2013). It appears that a given discipline has a customized definition of resilience. Broadly, resilience refers to the capacity of a system to tolerate disturbances while retaining its structure and function (Fiksel, 2003; Walker *et al*, 2004; IPCC, 2011). Given this, the review and study focused on system resiliency that emerges from the interaction and feedbacks from social, technical, and environmental components of irrigation systems. It is a dynamic and an innate property of the system; the functionality of existing "hardwares" and "softwares" (sensitivity) and adaptive capacity (adaptation measures) of irrigation systems affect system resiliency (Munasinghe & Swart, 2005). The buildup in system's intrinsic resilience accrues from the resultant influence of sensitivity and adaptive capacity of the system (Figure 2). A high resilience degree can soften the impacts of climate change stresses or shocks on irrigation system and the converse is true.

Adaptive capacity is the ability of a system to adjust its activity to cope with or resist stresses and episodic

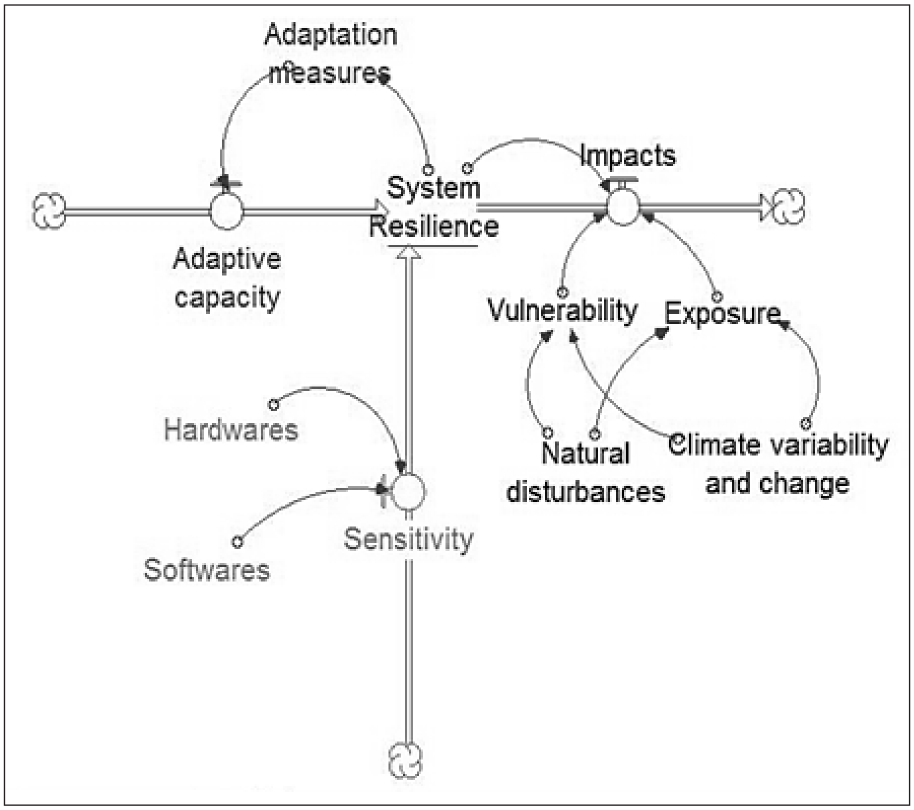

Figure 2. Framework for evaluating intrinsic resilience of irrigation systems through systems approach.

disturbance like drought or flood attributable to projected climate variability and extremes. Bolstering adaptive capacity builds up the resilience of irrigation systems through adaptation actions or measures taken by the system to counter the impacts of disturbances. Functional software and hardware components of the system can narrow adaptation gaps and contribute to system resilience; rehabilitating or replacing existing components will raise their functionality level. Furthermore, the system can innovate with "hard technologies" (e.g. irrigation technology like drip irrigation) and "soft technologies" (e.g., crop rotation patterns, improved varieties, and modified planting dates) to beef up innate system resilience. A successful adaptation strategy would typically combine both hard and technologies. I evaluated adaptation capacity through a holistic review of adaptation actions and interventions in the planning and design activities, in the operations and maintenance of the physical infrastructures, and in the social components.

Climate-related stimuli adversely or beneficially affect the sensitivity level of an irrigation system. Sensitivity is the degree to which a system is susceptible to injury, damage, or harm. I analyzed system sensitivity through the evaluation of the present functionality of designed and built facilities (hardwares and softwares) and by looking into past operations problems and damages experienced by irrigation systems. Therefore, there is a strong case for improving the resilience of infrastructure (McFarlane, 2015; Francis & Bekera, n.d.) to reduce potential damages.

In view, that government interventions or informal norms that regulate the use of irrigation and watershed ecosystems can modify exposure to hazards I externalized vulnerability and exposure to hazards, both determinants of impacts, in this study. Furthermore, in reality a system could be vulnerable to a hazard that is not present in a given system or that not all irrigation systems would experience identical hazards. That is the reason why this study focused on innate or intrinsic system resiliency rather than on specific system resiliency.

The database for this study consisted of published and unpublished research reports, feasibility studies, project completion reports, and ex-post evaluation reports. Likewise, it included results and outcomes from analysis of peer-reviewed publications on resilience, adaptive capacity, exposure, sensitivity, and vulnerability to climate change of irrigation systems particularly those in Asia. Meta analysis and synthesis of findings from available literature benefitted from approaches in resilience science, resilience thinking, and resilience management (Folke *et al*, 2010).

Field validation included a number of visits to relevant National Irrigation Administration's (NIA) central and regional offices and other government agencies.[2] I conducted comprehensive discussions on climate change adaptation and resilience of irrigation systems with hydrologists, planners, and personnel of the Project Planning, Design Specifications, and Construction Management Divisions of the Engineering Department. Similarly, I held discussions with those of the Irrigation Engineering Center of the Operations Department. The same conversations about irrigation systems resilience to climate change were held with engineers of the Project Management Office for Comprehensive Agrarian Reform Program—Irrigation Component. Also held, were discussions on climate change adaptation works at the NIA Regional Office 4-A, especially those that have to do with planning, design, construction, and operations. At the Design and Engineering Section, Water Resources Management Division, Bureau of Soil and Water Management (BSWM), the researcher carried out discussions on changes in design parameters of small-scale irrigation projects to accommodate climate change and climate variability.

Findings

The current degree of intrinsic resilience of most Philippine irrigation systems is plausibly rooted in the overoptimistic technical and economic assumptions and philosophy used during the planning and design process. Until recently the technology and principles of design applied to design and construction of irrigation schemes had changed hardly at all in 4,000 years (Laycock, 2007). Large deviations between design assumptions and operational realities, and design mistakes account for the chronic underperformance of irrigation systems because they severely curtailed irrigation systems' basic function to serve farmers on time with adequate irrigation water (Moya &Walter, 1988; Horst, 1998; Plusquellec, 2002; David *et al*, 2012; Tabios & David, 2014; PIDS, 2014). Laycock (2007) observed that various irrigation projects completed in the latter half of the 20th century rapidly turned into ecological and social disasters, and countless others never worked properly. For a long time, irrigation operators and researchers have considered poor water management and non-functional irrigation institutions the reasons for the inability of irrigation systems to function adequately (Mukherji *et al*, 2009; Wrachien & Goli, 2015). However, the nature of interaction and feedback between the social component (farmers, water institutions), physical subsystems, and irrigation processes (planning, design, construction, and operations and maintenance) plausibly accounts for the persistent irrigation system underperformance (Figure 1). The focus of research and investigation on the improvement of softwares only (social component) went on for a long time but the same problems did not only persist but became more challenging. Concentrating efforts on improvement of irrigation water management and leaving out issues and concerns in operations and maintenance and rehabilitation in the design, planning, and construction of irrigation systems is equivalent to treating the symptoms rather than taking the root cause of irrigation underperformance. Undetected and untreated, the shortcomings that inhere in the conventional planning and design process for hardwares (physical infrastructures) can amplify or aggravate problems occurring in other sub-systems or system constituents, especially the social and institutional components.

The foregoing is a clear evidence of a need for systems thinking and systems approach to figure out and solve the chronic underperformance of irrigation systems. Holistic solutions to irrigation problems should emerge from the consideration of dynamic interactions of components, processes, and feedbacks in an irrigation system. Moreover, it clearly shows that research and studies on irrigation should not have focused solely on the improvement of socio-institutional and water management components because that is a surefire way to destabilize the whole socio-technical system and engender unintended consequences. A neglect to consider irrigation system as a whole that is greater than the sum of its parts will lead to degradation in function, and thus erode system resilience to stresses and shocks (Wang *et al*, 2009). The functionality of water control and distribution structures and vibrant and participative irrigation community will lessen system sensitivity and increase resilience to extreme climate change anomalies.

Sensitivity of the Philippine Irrigation Systems to Projected Climate Change

Irrigation expenditures are substantial and biased toward rice. Irrigation investments have concentrated largely in the main rice producing areas of Luzon and Mindanao, Philippines. Nonetheless, only 1.678 million ha of the 3.1 million ha, or 55.59% of the total irrigable area in the Philippines have been developed for irrigation as of December 2013. About 92,000 different irrigation systems, which range in size from a few hectares to thousands of hectares,[3] supply water to the developed irrigated area. These irrigation systems fall into three water-delivery schemes: 1) run-of-the-river diversion, 2) storage or reservoir, and 3) pump irrigation.[4] Diversion or run-of-river systems draw controlled amounts of water from unregulated rivers or streams. Storage or reservoir systems impound water in dams and release it as needed by regulation or diversion dam downstream. Reservoir projects are usually multi-purpose to include other functions like power generation, flood control, fishery, and recreation. In contrast with the two schemes, pump irrigation systems lift water either from underground or from rivers and streams. Pump irrigation systems irrigate areas on higher elevation or bring up groundwater to augment low water flows in rivers thereby increasing system water availability and irrigation reliability.

In terms of management, the NIA conducts the affairs in national irrigation systems (NIS), the farmer community deals with those in communal irrigation systems (CIS), and individual farmers manage the privately owned systems. Each type accounts for 24.5%, 19.1%, and 6.5% of the total irrigated area, respectively (Table 1). An irrigation system can be a cross between water delivery schemes and form of management, like communal pump irrigation system.

Notwithstanding their differences in size, water source, water allocation and distribution schemes, operations and maintenance, and management institutions, these irrigation systems were designed and constructed based on requirements of rice irrigation systems (Mukherji *et al,* 2009). Thus, the existing irrigation systems will have limited operational flexibility to adapt to climate change, particularly when adaptation actions call for the planting of non-rice crops (Moya and Miranda, 1989).

Degradation of irrigation infrastructures. Adequate maintenance and rehabilitation of irrigation systems contribute to functionality of infrastructure and, thus to the resilience of irrigation operations staff and farmers to climate change hazards. Nonetheless, the low state of operations and maintenance (O&M)

Table 1. *Irrigated Area ('000 ha) Based on Census and NIA Data, Selected Years*

Year	Total	Gravity			Private		
		Total	NIS	CIS	Pumps	Individual	Others
Census [a]					-		
1991	2,296	1,275	736	539	-	626	395
2002	2,930	1,356	775	582		1,000	574
						(652)	
NIA [b]							
1991	1,580	1,428	668	760	152	-	-
2002	1,387	1,213	689	524	174	-	-
2012	1,675	1305	771	534	370		
2013	1,678	1316	740	576		195	

Sources: 1991 & 2002 Census of Agriculture, National Statistics Office; NIA, various years. Adapted from Inocencio, David, & Briones (2013).

result in major wear and tear leading to deterioration of irrigation facilities. Masicat, de Vera and Pingali (1990) observed increasing trends in degradation of irrigation infrastructure[5] in 92 national irrigation systems in Luzon, Philippines between 1966–1989. The sorry state of facilities attenuates system resilience to disturbance because it curtails the water conveyance, more so the water distribution, function of irrigation systems. More than 50% of control structures in both lateral and main canals of 157 out of 196 national irrigation systems studied were in need of rehabilitation and/or improvement; and more than 60% of main and lateral canals need de-silting, reshaping, and heightening of embankments (David & Inocencio, 2014; Inocencio, David & Briones, 2014). About three-fourths of the 13,967 km (close to 10,500 km) of irrigation service roads were in need of rehabilitation. In spite of the varied rehabilitation and maintenance works needed, the Delos Reyes (2014) study revealed that about 80% of the NIA rehabilitation projects were concentrated on lining of canals. Low irrigation service fee collection explains the chronic O&M backlogs that leave irrigation facilities in a state of disrepair.

Building and Strengthening Irrigation System Resilience

To relax operations inflexibility induced by design flaws, irrigation systems carry out adaptation measures to increase their hard resilience. The NIA installed afflux dike to raise river water elevation and spur dike to protect rivers from erosion to improve farmer service and thus enhance system resilience. In addition, the construction of new drainage system raised system functionality and drainage capacity to mitigate flooding and prevent waterlogging of farms. To arrest the fast buildup of sediments in reservoirs and thus lengthen their designed lifespan, NIA undertook replanting in watersheds, slope protection, and sediment extrusion from reservoirs (Table 3). Moreover, the NIA underscores the implementation of small river reservoir systems rather than purely diversion systems to cushion the drought impacts of climate variability, like El Niño.

Table 2. *Rehabilitation Performance of National Irrigation Systems*

By vintage	Avg. number of years before Rehab	No. of NIS with recorded Rehab
All systems	20	40
Before NIA	32	51
1965–1980	18	41
1981–1995	9	49
1996–2008	-	-

Source of basic data: NIA NIS database.
Adopted from: Inocencio et al, (2013).

Table 3. *Hardware Adaptation to Deal With Excessive Water and to Slow Down and Arrest Sedimentation in Irrigation Systems*

Flood control			Sediment control		
Intervention	Type	Usage	Intervention	Type	Usage
Pre-emptive spill	OI	High	Watershed replanting	PI	Low
Drainage rehabilitation	PI	High	(sediment control)		
Afflux dike	PI	High	Slope protection	PI	High
Drainage pumping	PI	Low	Silt extrusion	PI	High
Spur dike	PI	High			
Protection Dike		High			

Note: NB:OI = operational intervention, PI=physical intervention
Source: Labiano, 2014.

Table 4. *Comparative costs of different interventions*

Canal	Activity	DPR Head: tail ratio		Costs (US$)		Change in head: tail ratio	
		Before	After	(000$)	($/ha)	% change	% $/ha.
Khikhi	Lining	0.82	1.55	1,250	37.88	-57	-2
Pir Mahal	Major desilting	6.11	2.59	423	2.20	+ 144	+ 65
Lagar	Minor desilting	4.20	1.29	3.6	0.52	+ 225	+433

Sources: Murry-Rust. D.H. and Edward J. Vander Velde. 1994. Changes in hydraulic performance and comparative costs of lining and desilting of secondary canals in Punjab, Pakistan. Irrigation and Drainage Systems *8: 137–158, 1994.*

Canal lining. Lining canals is a major component of irrigation system rehabilitation works to reduce seepage losses in irrigated agriculture. Canal lining technologies (Rohe, 2004; Riaz & Zen, 2005; Stark & Hynes, 2009) appropriate to climate change current risks and vulnerabilities of irrigation infrastructures require detailed assessment and study. Carbon-fiber-reinforced-polymer (CFRP) is available for rehabilitation of steel components of irrigation infrastructure to address corrosion. Similarly, to retrofit and strengthen masonry structures, the agency can use fiber-reinforced-polymer (FPRP) or other new materials to address de-bonding failures. In the Philippines, concrete is normally the material used for lining irrigation canals.

Regardless of lining materials used, canal lining does not guarantee that real water savings will ensue from this costly rehabilitation endeavor. Results of intensive studies, from countries like Pakistan that undertook extensive canal lining with concrete, showed results that run counter to expected water savings (Murray-Rust & Vander Velde, 1994). Water distribution inequity not only persisted but it worsened after concrete lining of distributary canals (Table 4).

Also in terms of maintenance costs per hectare, even with a life span of 20 years, canal lining costs 20 times more than cleaning and desilting of canals (Murray-Rust & Vander Velde, 1994). As an adaptation measure to increase water use efficiency, concrete lining of irrigation canals to prevent leakage is at best a doubtful suggestion and at worst could be a maladaptation to climate change. The apparent water saved from canal lining comes at the expense of lowered groundwater level that could undermine NIA's shallow tubewell irrigation programs to augment short water supplies. What was leakage to the irrigation operator is recharge from the viewpoint of the well owner and user. Many irrigation experts noted that although canal lining has been a feature of a conventional suite of recommendations in many foreign-funded irrigation projects, the justification must be backed by appropriate economic and water balance studies.[6]

In view, that lined canals do not show constantly low seepage rates throughout their operating life, concrete lining or lining of canals in general must be carried out only where otherwise substantial seepage losses would be inevitable.[7] The extensive concrete canal lining program that NIA goes in for now must be appraised further to determine whether "real water" can be saved to adapt to expected drought impacts or to open up new areas for irrigation. Irrigation canals, lined fully from main to lateral to farm ditch, do not guarantee efficient farm water allocation and distribution. Furthermore, the irrigation agency must carry out *in situ* experiments and assessments before blanket concrete lining of irrigation canals.

Rotational water distribution. Measures to enhance system's soft resilience to scarce water supply thanks to climate change are operational already in some irrigation systems (Table 5). Harvesting and storing rainfall and runoff in ponds and reservoirs during the rainy season is a countermeasure against the negative impacts of droughts on crop production. The NIA operations staff can readily shift from designed continuous to rotational irrigation to optimize distribution of scarce water supplies during drought episode. Complementary to this, drainage re-use systems are built to capture water distribution losses to increase water use efficiency. NIA retrofitted offtakes using a simple weir as cross regulator and notched weir with gate shutter as intake for ease of operations. In sum, the NIA has been building operational redundancies to build resilience to water impacts of climate change.

Table 5. *Hardware and Software Interventions to Water Shortage Problems*

Water augmentation			Water conservation		
Intervention	**Type**	**Usage**	**Intervention**	**Type**	**Usage**
Drainage reuse	PI	High	Rotational irrigation	OI	Medium
Transitory ponds	PI	Low	Farming system	OI	Medium
Shallow tubewell	PI	High	Canal lining	PI	High
Stream tapping	PI	High	Offtake retrofitting	PI	High
Reservoir dams	PI	High	Controlled irrigation	OI	Medium
			Cropping pattern	PI	Medium

Note: NB:OI = operational intervention, PI=physical intervention.
Source: Labiano, 2014

Alternate wetting and drying. The agency encourages farmers to practice alternate wetting and drying (AWD) to save water. AWD, an alternative irrigation technology, directly relates to rotational irrigation. In this practice, the crop is intermittently submerged and dried from 20 days after sowing until two weeks before flowering. Farmers drain their fields until water below the surface reaches down to 15 cm before re-flooding. Hence, farmers' fields are alternately wet and dry during the crop irrigation season. The number of dry days between irrigations can vary from 1 to more than 10 days depending on a number of factors, such as soil type, weather, and crop growth stage. A number of irrigation systems in the Philippines introduced and adapt AWD to economize short water supplies or even save water. Given these specific field requirements, AWD clearly requires that irrigation water distribution be carried by turns or rotation by the irrigation system. The viability and sustainability of widespread adoption of AWD in irrigated systems necessitate system-wide operations studies to determine appropriate management feedbacks to implementers. Irrigation practitioners must explore first the synergy (or interference) of system-farm interaction and processes in implementing AWD. Without changes in the system, farm-level physical control, and distribution facilities, real water savings from AWD is hard to come by. AWD may reduce rice crop requirements in the field but it will plausibly entail high system water losses, especially if scarce water conditions would require rotational irrigation at higher canal levels. Although AWD adopters expect to save as much as 25% water, a number of AWD studies have yet to show any real water saved from the application of this technology. Currently, AWD could be a maladaptive measure to water scarcity impact of climate change; thus, would-be adopters must evaluate it more carefully in terms of systems operational requirements.

Conjunctive water use. Another irrigation innovation that can improve the adaptive capacity, and, thus, reduces the vulnerability of irrigation systems, relates to developing integrated rainfall harvesting and groundwater policies extending from small-scale to large-scale infrastructure. So long as water tables are accessible, groundwater can counteract the vagaries of erratic rainfall and uncertain water supplies. Shallow-tube wells and low-lift pumps are widely used for irrigation in Asia, notably in India and the Philippines. In the Philippines, farmers at the tail end of large irrigation canals use shallow tubewell irrigation systems to hedge uncertain and inadequate water supplies; like those expected under climate change.

Complementing conjunctive water use is the development of cheap pumping technologies that have led to the proliferation of unregulated pump irrigation and groundwater use in Asia. Atomistic irrigation[8] has been a significant development in the past decades. It accounts for 39 million ha and 19 million ha irrigated by groundwater respectively in India and China or it accounts for 40 percent of actual irrigated area in the world (Siebert *et al*, 2010). Different forms of atomistic irrigation may be better suited than communal irrigation schemes for areas with high population growth, acute poverty, and isolation from markets, for instance, the Visayas region of the

Philippines. There appear tremendous potentials of atomistic irrigation systems in rainfed areas.

Conjunctive use of canal water and groundwater will remain an attractive option to enhance operational flexibility and increase irrigation supply reliability; it offers large potentials for improving irrigation system resilience to climate change. Solar-powered irrigation pumps are being used around Asia, particularly Bangladesh and India. In the Philippines, solar energy companies have also been developing modular solar-powered pumps for irrigation and other uses. Irrigation system planners and designers, who wish to strengthen resiliency of irrigation systems, must consolidate small-scale farmer-controlled irrigation systems with large rice-based irrigation systems.

Farmer-Controlled Small-Scale Irrigation Systems

Developing a number of small-scale irrigation systems or a multitude of individual or atomistic irrigation systems can be an option to developing large irrigation systems. Small-scale irrigators adapt to recurrent disruptions in the irrigated environment because they can optimize use of rainfall, return flows, uncontrolled supplies, and so forth. Farmers in these systems have autonomous control over irrigation operations so they have the flexibility to cope with rainfall variability and uncertainty; thus, they can be resilient to climate change risks.

To raise the reliability of inadequate and uncertain water supplies, irrigation system planners and designers must innovate to incorporate farmer-controlled irrigation systems into large irrigation systems. These include shallow tubewells, small inundation schemes, farm reservoirs and low-lift pumps, mini ponds, farm ponds or small water impounding reservoirs, or the melon-on-the-vine systems (Food and Agriculture Organization, 2007). Small irrigation system require much less investment, have very short gestation periods, yield higher productivity, give farmers a greater degree of control over their irrigation water, and are more amenable to crop diversification (David, 2003). The small structures store water from larger irrigation canals or catch drainage water and re-use it when canal water supplies and rainfall become unreliable. Notable innovations include “melon-on-the-vine” system in the Zhanghe irrigation system in South China (Roost, Cai, Turral, Molden & Cui, 2008); tank systems in South India and Sri Lanka; and *diggis* in Rajasthan’s Indira Gandhi Nahar Pariyojana (IGNP). In addition to improving operational flexibility, the melon-on-the-vine system of the Zhanghe irrigation system reduced nutrient contents of drainage water (Dong *et al*, 2009). The results from both pond survey and field experiments revealed that the melons (ponds) are suited to collect and reduce nutrient loads of field drainage water. The tanks, *diggis*, and melons (ponds) not only enhance operational flexibility of the system but also prevent pesticide and fertilizer pollution. In addition, they recharge groundwater for shallow tubewell users.

Resilience in Planning and Design

In many countries, structures are designed using national building codes and infrastructure standards. These codes and standards depend on a set of climatic and seismic design values that can vary from one location to another. Almost all the infrastructure today has been designed using climatic design values calculated from historical climate data under the assumption that the average and extreme conditions of the past will represent conditions over the future lifespan of the structure (Wrachien & Goli, 2015). While this assumption has worked in the past, it will no longer hold because climate has been changing virulently. It will become important then to regularly update climatic design values to reflect the changing climate and that deficiency in existing climatic design values are improved. Both safety and economics influence decisions on how to build structures. Irrigation planners and designers must consider realistic estimates of future climatic design loads to come up with an appropriate balance between safety and required strength, serviceability of the structure, and initial and maintenance costs. While structures can always be “over-designed” to protect against natural hazards, the economic costs to societies can be prohibitive enough to constrain irrigation development.

Climatic design values include quantities like the 10-, 50-, or 100-year return period for “worst storm” wind speed, rainfall or weight of snowpack are typically derived from historical climate data. Other climatic design quantities include percentile cold, hot, or humid temperature or humidity conditions, return period of ice accretion loads and average degree-day quantities. A given return period of a storm refers to the risk of it being reached or exceeded in a period; it does not mean that the design storm only occurs once in a given time period. Rather it means that the design storm can occur anytime within a return period.

Design process in Philippine irrigation systems. Design standards and operation for irrigation systems have not changed in many countries for 20 to 30 years. Irrigation planners and designers of most irrigation systems in the world designed and developed them in phases with a lifespan of 50 years or longer (Plusquellec, 2002). Design standards, for the projects supported by the United States Bureau of Reclamation (USBR) in the Western States, are the most detailed standards used worldwide. The basic design consists of a network of canals equipped with water control and distribution structures that irrigation personnel control manually. They have been widely disseminated through technical assistance and consulting firms to a number of developing countries. In some of these countries, such as Thailand, the Philippines, Mexico, and Turkey, U.S. Bureau standards have become de facto national standards for a few decades. Countries without national standards used the USBR design standards for specific projects (Plusquellec, 2002).

In the Philippines, the design of irrigation structures and appurtenances is based on the USBR procedures and on international design standards brought in by consultants for foreign-funded projects (Moya, 2014). For example, the stability analysis and embankment design of Bayongan dam of the Bohol Irrigation Project, Stage-2 (BHIP-2) depended upon the "Design Criteria of Dam Design" of the Ministry of Agriculture Forestry and Fisheries, Japan in combination with the USBR standards. To determine dam crest elevation, designers used the probable maximum flood (PMF) equivalent to 1/1,000 year, according to the Japanese Design Criteria for Fill-type Dam. By this token, there are a number of design codes and standards resulting from permutation and combination of the USBR design assumptions and guidelines, international standards especially those brought in by consultants of foreign-assisted projects, and from experiences of NIA design engineers and personnel.

However, foreign engineers, who produce designs of new irrigation schemes or who supervise construction, are rarely involved in the operations and management of the completed schemes. They might not know the many operational and field problems the constructed systems brought onto field personnel due to the design flaws. In that case, they could miss an opportunity to hear and learn feedbacks on the shortcoming of their design assumptions and methods from the operations and maintenance personnel. The chronic underperformance of most irrigation systems is rooted upon the design flaws that end up in schemes deteriorating quickly and needing early repairs and rehabilitation. This will claim a high stake in the resilience of irrigation systems because it will limit flexibility and adaptive capacity of the constructed systems.

Design under climate uncertainty. Irrigation engineers at the NIA have been planning and designing irrigation structures and facilities for large irrigation schemes based on a 50-year return period. Those from the Bureau of Soil and Water Management (BSWM) plan and design dams and appurtenant structures for small-scale irrigation projects according to 25-year return period. Now, thanks to potential risks from climate change and variability, the NIA irrigation engineers plan and design irrigation structures and facilities based on flood magnitude of a 100-year return period and those of BSWM on flood magnitude of 50-year return period.[9]

The increase in flood design standards[10] to accommodate larger risks from climate change determines the size and quality of resulting new irrigation structures and facilities. Effectively, the increment in design standards inflates the cost of an irrigation project. A study by the United States Bureau of Reclamation (USBR) pointed to a 100-percent incremental costs to build dams and appurtenant structures from floods with 50-year to 100-year return period. Similarly, costs of small-scale irrigation projects will double up for design flood from 25-year to 50-year return. To be resilient to higher uncertainty and risks from climate change will warrant a steep increase in project costs and could create significant ripple effects in other sectors. To alter the design standards—to enhance system capacity to absorb and to some extent to avoid potential impacts from climate change and variability—involves careful modeling and optimization studies because the change can create risks to irrigation development.

Designing resilient irrigation system ought to consider the big picture, that is, it is a complex system of sub-systems. By interposing water conservation structures between the supply and demand subsystems, irrigation planners and designers will increase the

Table 6. *Estimated Incremental Changes of Costs; Appurtenant Structures for Dams (Spillways and Outlet Works).*

Flood return period (years)	Total Diversion System Cost > 2 year flood (CD)	Total Probable Flood Cost (CF)	Incremental Change of Total Diversion System Cost (ΔCF)	Incremental Change of Total Probable Flood Cost (ΔCF)	Percentage change in cost diversion system	Percentage change in cost probable flood
2	$0	$1,727,494	--	--	--	--
10	$100,000	$453,611	$100,000	$1,273,883	--	-73.74
25	$300,000	$188,132	$200,000	$265,479	200.00	-58.53
50	$700,000	$95,186	$400,000	$92,946	133.33	-49.40
100	1,500,000	$47,873	800,000	$47,313	114.29	-49.71
200	$3,100,000	$24,007	$1,600,000	$23,867	106.67	-49.85
500	$6,300,000	$9,620	$3,200,000	$14,387	103.23	-59.93

system adaptive capacity. The synergy that will emerge from the interaction of processes within and among the sub-systems will increase system resiliency to droughts or floods. Melon-on-the-vine (ponds, tanks) will recharge groundwater to bring on conjunctive water use for shallow tubewell pump irrigation. In addition, these structures will increase system's capacity to mitigate floods in the service areas. Apart from irrigation and drainage use, farmers can augment their incomes by growing fish in the ponds and tanks and, thus, become more economically resilient. Furthermore, strong competition among users for scarce water calls for designing irrigation systems for multiple water uses. On multiple use systems, dam designers must factor in the impact of droughts on processes affected by low water level, like hydropower generation. The increased frequency and severity of droughts due to climate change could make hydropower generation more undependable and a costly source of energy. Energy problems can affect the resiliency of other socio-technical systems, such as industries and urban cities. The design philosophy to include complex system principles in new large irrigation projects and modernization of existing ones have great potential to increase capacity to absorb and adapt to impacts of shocks from climate change.

Furthermore, irrigation planners should begin with farmers' needs in mind in the design of resilient irrigation projects. Gaining sustainable economic benefits from irrigation infrastructure depends not only on reliable water delivery structures but also on institutional capacity to operate and maintain the systems (Fishbein & Haile, 2012). Sustainable income from irrigation will encourage farmers to pay irrigation service fee to keep up maintenance and operations of physical infrastructures.

To a great degree, strong system resilience to emerge out of synergy between farming systems, irrigation systems, and watershed necessitates that irrigation planning and design philosophy shift from conventional project-focused design to Integrated Water Resources Management (IWRM) philosophy and paradigm. The integrated planning and design becomes critical as more and more watersheds and basins become "closed," that is, all water resources in the watershed are fully committed and no water of unusable quality is flowing to the sea.

End-User Involvement in Irrigation

Investment in irrigated agriculture can benefit the poor if they are included in the design of the projects, if they participate in the management of irrigation systems, and if they gain new economic prospects (Plusquellec, 2005). A generic component of adaptation package to climate change in rice-based irrigation systems is to switch to high value, low-water consuming non-rice crops not only to save water but also to increase farmer incomes. However, rice irrigation systems, with a designed low density of on-farm irrigation ditches and farm drains, are sufficient for field-to-field rice irrigation but it could limit the productivity of non-rice crops. Non-rice crops need direct-plot access to irrigation and drainage that provide intermittent water supply and keep soil from water logging (Plusquellec, 2005). Thus, the density of farm water control and distribution facilities in existing irrigation systems will be inadequate for farmers to grow and harvest non-rice crops under climate change[11] (Moya, 1979; Moya & Miranda, 1989). Due to the lack of detailed farm information, field water control and distribution facilities were either wrongly placed or misaligned. The design deficiency limits operational flexibility of both field irrigation personnel and farmers to adapt to risks brought about by climate change. Farmers possess detailed knowledge about the topography and the complex interaction of crop production with the biophysical setting of their farms. They must be involved or at least consulted in the design of on-farm irrigation and drainage facilities and structures to include operational flexibility for growing non-rice crops.

Opportunities for Strengthening System Resilience

To meet farmers' irrigation needs adequately, most irrigation systems in the Philippines and Asia, need to modernize their systems. At a regional consultation in FAO Bangkok in 1996, consultants defined irrigation modernization as "a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes with the objective to improve resource utilization (labour, water, economic resources, environmental resources) and the water delivery service to farms" (Renault, 1998). Irrigation modernization exacts total revamp of irrigation socio-technical system, which involves upgrading of both technical and social components (managerial) of existing irrigation systems. Modernized irrigation systems will require investments in the update and upgrade of hardware (technical) and software (social) components of the irrigation systems. On the one hand, hardware investments must go beyond the simple rehabilitation of physical infrastructures in existing systems but it should also consider on-farm irrigation technologies such as drip irrigation, and a drainage network. The water delivery systems in most existing systems that had been designed for single use should be adapted for multiple uses to be resilient to changes in water allocation. On the other hand, software investments include scheme management and institutional structures; and on-farm water management practices for crop, land, and water. Moreover, the increasing competition for water from other socio-technical systems in a given watershed, such urban, agricultural, industrial, and environmental systems, prescribes a need for integrated water resources management.

To sum up, with the integration of systems principles in designing adaptation bundle for irrigation modernization, new irrigation projects and existing irrigation systems will be resilient to impacts of projected climate change. A "modernized irrigation" should be an overhauled irrigation system capable of adapting to recurrent operational disruptions and to hydro-meteorological risks from climate variability and change. The Agricultural and Fisheries Modernization Act (AFMA) provides modernization opportunities to Philippine irrigation systems.

Resilience From Healthy Watershed Ecosystem

Similar to any technical subsystem introduced into a social-ecological system,[12] irrigation system uses water and other goods and services provided by a watershed, where many other competing socio-technical systems are situated. The state of health of the watersheds influences the hydrology of rivers and groundwater aquifers that feed water to irrigation systems, which in turn is delivered to farmers' field. A healthy watershed ecosystem can strengthen the resilience of systems co-located in it; they form the first line of defense of irrigation systems from impacts of climate change. Watersheds are natural infrastructures for adaptation or even for mitigation of climate change impacts. For effective and stronger adaptation to climate change, the water regulation and storage function of watersheds can improve system synergy, thus strengthening system resilience to repeated disruptions and catastrophic events. Irrigation systems must harness the goods and services provided by the natural (green) infrastructures in a watershed. Considering the natural infrastructure over the engineered infrastructure will enhance the adaptation synergy of the socio-technical sub-system and the ecological system to reduce vulnerability or strengthen system. Overall, the watershed resiliency is a mitigation strategy. As such, the synergy between adaptation measures in irrigation system and natural mitigation strategy of watershed can greatly heighten irrigation system resiliency.

Thus, the NIA realizes the connectedness of the irrigation system functions, especially water regulation and storage, to the health of watersheds to sustain adequate and reliable water supplies to farmers.

Furthermore, watersheds can protect existing irrigation systems from drought and flood impacts, so they can provide uninterrupted service even under climate change. In view of the foregoing, the NIA's Strategies and Action Plans 2014-2020 includes management and protection of watersheds where irrigation systems are located.

Capacity to Learn and Self-Organize

Organizations, like the NIA, has the capacity to distill experiences and learn to adapt to stresses and shocks. The capacity building of the irrigation profession at large partially explains the chronic underperformance of most irrigation systems; and a critical action is the revision of design standards (Plusquellec, 2002). To this end, the National Irrigation Administration organizes trainings, seminars, and workshops to update and upgrade design knowledge and skills of its personnel. The NIA held a seminar-workshop on the Design of Irrigation Projects for new design engineers and other persons involved in the design of irrigation projects in support of the Department of Agriculture's Rice-Self Sufficient Philippines 2013. Elite and learned resource persons from the NIA and engineering consultant groups discussed the processes and significance of conducting feasibility study, designing irrigation and drainage canals and canal structures, designing diversion works, and designing embankment dam.

The capacity to absorb and adapt to impacts of climate change and variability will greatly improve with a vibrant research division. Irrigation research, particularly on design parameters and standards, should be encouraged because adaptation to climate change is a continual process. Threshold values of conveyance water losses that warrant concrete canal lining should be borne out of canal ponding experiments in existing irrigation systems.

To facilitate the integration of climate change in NIA, it includes plans in its NIA's Strategies and Action Plans 2014-2020 to conduct information dissemination, workshops/seminars on the effects of climate change on design standards, technical innovations, and adaptation and mitigation measures. The NIA will continue to update and upgrade skills and knowledge of its human resource in tie-up/coordination with institutions providing scholarships here and abroad. The collaborative work with other institutions will provide social (agency) enhanced capacity to deal with predicted climate change impacts and, and thus strengthen irrigation system resiliency.

Summary

In summary, the overoptimistic technical and economic assumptions and design philosophy used in planning and design had plausibly compromised the intrinsic resiliency of most Philippine irrigation systems. This stems partially from the failure to consider irrigation projects from the viewpoint of systems science and practice—that irrigation systems are socio-technical systems with interacting components, processes, and feedback from which emerge important system attributes, like resiliency. The system structure dictates system function. For a long time, this neglect to look at irrigation systems from systems viewpoint resulted in chronic underperformance that weakened functionality and renders most of them intrinsically vulnerable and, therefore, less resilient to too little or too much water or both, projected from impacts of climate change and climate vulnerability.

The design, construction and operation of existing Philippine irrigation systems did not take parameters derived from extreme climate change events. *Per se,* the capacities and state of current irrigation facilities could not handle the flood and drought anticipated from climate change, making them sensitive to climate change extremes. Adapting adequately to probable impacts of climate change necessitates modification in design codes and standards for new irrigation projects and rehabilitation of existing irrigation systems. However, the irrigation agency must conduct exhaustive studies and research on optimum design parameters according to magnitude and intensity of uncertainties associated with current climate projections. A doubling of the current design return period will result in the doubling project costs; hence doubling of project cost may influence the parameters used in the traditional benefit-cost analysis and in the technical approaches to irrigation development. Otherwise, this situation can constrain design and construction of new irrigation projects, and thus limit growth of irrigated areas.

Irrigation agency should begin planning and designing irrigation projects with the farmers' needs and experiences foremost in their mind. Designing operational flexibility into irrigation systems may call for reconfiguration of conventional irrigation system to interpose melon-on-the-vine (ponds, tanks) and shallow tubewells between the main irrigation system and the farm. Alternatively, atomistic irrigation should be encouraged within the command area of large irrigation systems to complement system water supply reliability (Facon & Mukherji, 2010). Privately owned and operated, small shallow tubewell irrigation systems give farmers operations flexibility and ease of maintenance; they will increase farmer and system adaptation capacity to impacts of climate variability. The introduction of these small infrastructures can increase system capacity to absorb or cushion the stresses and shocks from climate change. On multiple use systems, dam designers must factor in the impact of droughts on processes affected by low water level, like hydropower generation. The increased frequency and severity of droughts expected from climate change can make hydropower generation more undependable and costly source of energy. Other socio-technical systems that depend on dependable energy supply, like urban and industrial cities, will bear the consequences of erratic energy supply. More importantly, the design irrigation parameters must not compromise the ecological integrity of aquatic and terrestrial ecosystems to interfere in their production of goods and services for the socio-technical systems.

To deal with the capacity limitations of existing irrigation facilities, the NIA has been carrying out operational and physical interventions to augment, conserve, and reallocate scarce water supplies by lining irrigation canals, practicing rotational irrigation, and adopting AWD technology, among other measures. However, without adequate evidences from studies and field investigations to justify implementation, the said interventions can become maladaptive measures. At the larger scale, adaptive measures to expand water supply imply building more reservoirs, transbasin transfers, and diversion and pumping groundwater. These measures all impinge upon the health conditions of the watershed. To improve resilience, the NIA should invest in watershed green infrastructures as a mitigation strategy to enhance adaptation options of irrigation systems and ultimately that of farming communities.

Recommendations

Being a socio-technical system, the analysis and synthesis of intrinsic resilience of irrigation systems to disruptions from climate variability and change will benefit from systems dynamics study approach. The outputs and outcomes from the review ensued from the internal dynamics of socio-technical systems to bring about factors that strengthen or weaken adaptive capacity of irrigation systems. The structure of the system dictates function, that is, to serve the farmers with water; continuous system functionality determines system resiliency. It follows that a holistic view of adaptive capacity and of changes in functionality will delineate system resiliency. Following are recommendations from this review.

1. Analyze and synthesize irrigation issues and problems from a systems viewpoint, that is, an irrigation system is a system of systems and is more than the sum of its parts.
2. Proceed cautiously with the revision of design codes and standards because the impacts of the revision can ripple upstream and downstream to influence adaptation options for other sectors to climate change. Encourage irrigation research on design standards because adaptation to climate change is a continual process.
3. Conduct (simulation) studies on interposition integrate melon-on-the-vine system (pond), *diggis*, and small tanks between the main system and the farm to evaluate adaptive capacity enhancement from the interposition of these small structures. When proven beneficial to improve systems' adaptation capacity to climate change, irrigation planners and designers should include them in their design philosophy and approach.
4. Evaluate the viability of atomistic irrigation systems and other small-scale, farmer-controlled irrigation systems for conjunctive surface-ground water use in rainfed and irrigated systems. There exist possibilities to improve and enhance the adaptive capacity, hence resilience, of irrigation systems.
5. Begin and end irrigation project/system planning with adequately meeting farmers' needs foremost in minds. Ensure that the farmers will be involved preferentially in

the planning stage of an irrigation system. Irrigation planners and designers should pay serious attention to the provision of farmers with adequate on-farm irrigation and drainage facilities. In the same manner, retrofit the water delivery systems to accommodate multiple uses of water from urban, agriculture, and municipal water demand.

6. Canal lining, to control irrigation water loss in water delivery systems, accounts for a major investment in irrigation rehabilitation/operation. However, with inadequate evidence from *in situ* research to back its necessity up, concrete canal lining can become a maladaptive measure to counteract climate change impacts.
7. Encourage the NIA's to get involved in or even spearhead the rehabilitation and protection of irrigation watersheds as green or natural infrastructures. Healthy watersheds form the first lines of defense of irrigation systems and agriculture to climate risks.
8. Continue to capacitate irrigation personnel to enhance the adaptive capacity of most irrigation systems.

Notes

[1] In some irrigation literature, the physical infrastructures comprise the "hardwares" and the "softwares" consist of social components and the rules and processes used in the operation of hardwares.

[2] Other Philippine agencies, the Department of Agriculture (DA), Department of Environment and Natural Resources (DENR), Agricultural Training Institute (ATI), and Philippine Crop Insurance Corporation (PCIC) jointly undertake development of adaptation countermeasures to climate change impacts in agriculture and natural resources management.

[3] Estimated from irrigation statistics from the Cagayan Valley Region, which has 13,840 different irrigation systems that cover 251,598 ha of agricultural lands.

[5] Irrigation infrastructure degradation was measured by changes in service area covered by irrigation (Masicat et al., 1990).

[6] Canal lining is extremely popular with both the donor agencies and recipient governments. They provide the donors with an opportunity to meet lending targets and irrigation agencies with the opportunity for "skimming" or what is politely referred to as rent-seeking (Repetto, 1986)

[7] When NIA engineers were asked about the threshold conveyance efficiency or percentage conveyance water losses that occur in a certain canal before it warrants concrete lining, no exact values were given. Real water savings from this costly endeavor will be difficult to determine later.

[8] Atomistic irrigation, as defined by Tushaar Shah (2008), refers to farmers using locally adapted technologies to scavenge water from surface water and groundwater.

[9] Although local government units (LGUs) implement the construction of communal irrigation systems, the design is prepared by the NIA. Design of some farmer-managed small-scale irrigation systems, like SWIPs, is undertaken by BSWM.

[10] Corresponds to increase in design return period of climate events.

[11] The density of tertiary irrigation systems, required for non-paddy crop cultivation, depends on factors including land slope, nature of soils, farm size, mechanization, and method of on-farm water application.

[12] Well-functioning watersheds and intact floodplains and coasts provide water storage, flood control, and coastal defense.

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