Strategic Use of Groundwater-based Solutions for Drought Risk Reduction and Climate Resilience in Asia and Beyond

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Introduction

Drought is a natural form of water scarcity resulting in a temporary imbalance of water availability of uncertain frequency, duration and severity, primarily caused by persistent lower-than-average precipitation (Santos Pereira et al., 2009). Operational definitions identify meteorological drought, agricultural drought, hydrological drought, socio-economic drought, and ecological drought (Wilhite, 2000) but groundwater drought is a consequent hazard, with delayed and complex responses (Calow et al., 1997, UNESCO, 2011). Groundwater drought is the manifestation of the meteorological drought in the subsurface and linked system. It is characterized by decline in groundwater recharge, storage and discharge due to general groundwater level decline (Villholth et al., 2013). Droughts are expected to intensify in future due to the global warming from greenhouse gas (GHG) emissions (Mondal and Mujumdar, 2015). Droughts are not only intensifying, but they are also spreading into territories where droughts used to be less intense and relatively infrequent. Several locations in South East Asia (SEA), considered one of the water-rich regions in Asia, were severely affected by drought and water scarcity during the 2015 and 2016 El Nino (Thirumalai et al., 2017). Elevated levels of malnutrition is anticipated in Asia from the risk of drought related water hazards and food shorage and reduced crop productivity (IPCC, 2014). How are the countries in Asia going to prepare against the intensified drought risks is a crucial question.

Groundwater is a de-facto source of water during drought and emergencies (UNESCO, 2011). In Japan, groundwater supply was an effective countermeasure against emergency after the Hanshin-Awaji earthquake (1995) and the Great East Japan Earthquake (2011). A registration system for citizen-owned and company wells became the basis for cooperation for water supply during these emergencies (Tanaka, 2016). Similarly, the promotion of groundwater use by distributing or constructing borewells was one of the key responses by the ASEAN member states (e.g. the Philippines, Indonesia, Viet Nam, Myanmar) to support farmers affected during the 2015-16 El Nino induced drought (ASEAN and JICA, 2017). A simple act of digging wells, where conditions and groundwater resources allow, can be useful to reinstate a stable supply of water and mitigate drought (UNESCO, 2011). Availability of groundwater storage could insulate the people and their livelihood in areas exposed to the metrological drought although prolonged drought, truning into groundwater drought, could compromise groundwater quantity and quality and excerbate already ongoing degradation. For instance, during 2009 drought, when rainfall deficit was 33% and 66% in Punjab and Haryana, the reduction in irrigated paddy area was only 0.7% and 10%, respectively, because of intensive groundwater use (Mukherji, 2018a). However, depending on the context, there could be several “push-and-pull” factors for accessing groundwater, which will ultimately determine the practical utility of groundwater to deal with water scarcity (Shivakoti, 2016). Ubiquitous availability, ease in access, vast storage potential, and reliable supply and quality are the “pull” factors attracting people towards groundwater. The pull factors make groundwater an ideal resource for drought mitigation. “Push” factors are unfavourable conditions when people have no other option than to resort to groundwater supply under constrained situation such as when exracting and assessing groundwater is expensive or involve helath risk due to poor water quality (humana and geogenic contaminiation).

A re-evaluation of the default role of groundwater for long-term drought mitigation as well as for short-term emergency is necessary due to two trends. Firstly, the use of groundwater is expanding due to increasing water scarcity and competition from multiple sectors. Cities, industries and farming communities in Asia are using groundwater extensively in an unplanned manner, often by the user’s initiative (Kataoka and Shivakoti, 2013). Over the past decades, there has been an explosive growth in agricultural groundwater uses in Asia (Mukherji et al., 2009). For instance, groundwater supports over 50 per cent of irrigation and 85 per cent of rural drinking water in India, which is the largest user of groundwater in the world (Das and Burke, 2013; Giordano, 2009). As a result of continued groundwater development, aquifers could dry out and eventually lose their inherent buffer, i.e., their potential for drought risk mitigation. Secondly, the recharge conditions could be negatively affected due to land use and land cover changes, such as an increase in impermeable areas in cities, and land degradation. Increased abstraction coupled with altered recharge conditions could threaten the resource sustainability. Climate change will indirectly exacerbate the pressures on groundwater resources because it will be increasingly resorted to supplement the temporal deficit in water supply due to the change and larger variability in precipitation and runoff. Global warming is leading to a hydroclimatic regime shift toward more intense and less frequent precipitation events, which would increase the risk of both flood and drought (IPCC, 2014).

In a broader perspective, the traditional short-term strategy of using groundwater to combat water deficits during drought needs revisiting. With climate change, there is a need to integrated disaster risk reduction (DRR), climate change adaptation (CCA) and mitigation approaches to recurrent and consecutive multi-hazards , in particular floods and droughts. As a part of this paradigm shift, groundwater and subsurface could serve as strategic natural water infrastructure for DRR and for building resilience towards both floods and droughts. The objective of this paper is to examine the relevance and options for developing and adopting such groundwater-based natural infrastructure (GBNI) solutions in DRR strategies. While addressing emergency situations, such solutions may also serve to enhance the sustainable use and management of groundwater as a strategic resource for long-term drought risk reduction as well as enhancing the resilience of farming systems and groundwater dependent cities and natural ecosystems.

Using groundwater storage for drought and flood risk reduction

It is getting increasingly common in several parts of Asia that a location affected by floods in one period will suffer from prolonged drought at another time. The concentration of annual precipitation amount in a fewer and intense rainfall events not only induces flood hazards, but the short residence of runoff water could negatively affect the aquifer recharge depending on the state of land management and hydrogeological properties. A hydrological perspective is therefore desirable to co-manage high and low flow conditions. As an example, Japan's new Basic Law on Water Cycle (2014 Act No.16) aims to maintain and restore sound water cycle management and fully take into account the impacts on surface water and groundwater (Shivakoti, et al, 2015). The Yangon Declaration, an outcome of the 3rd Asia-Pacific Water Summit, has also stressed on the need for a sound water cycle management, including the promotion of green infrastructure and nature-based solutions for DRR (APWF, 2017). These new paradigms are in line with the World Water Development Report of 2018 entitled Nature-based Solutions for Water (UN-WWAP, 2018)

An integrated approach is necessary for reducing the risks from the multi-hazards resulting from hydrological imbalances. For instance, in the case of surface water resources, integrated dam operation and management or construction of multi-purpose water storage dams could be employed to mitigate the drought and flood risk. However, regulating dam water levels could be associated with increasing risk with the increasing uncertainty regarding the frequency, timing, intensity and duration of rainfall. Besides, dam storages for droughts and floods are mutually competitive, the former favouring maximising storage and the latter favouring retaining space to enahle storage of excess runoffs during the floods. Higher than average rainfall and sudden release of a huge amount of water around the end of October after reaching of storage capacity from two major reservoirs (the Bhumibol and Sirikit dams) were lead causes for the 2011 flood in downstream Chao Phraya River Basin, Thailand (Singkran, 2017). Above all, the construction of dams is expensive, time-consuming, and often controversial due to unintended social and ecological impacts. The option for building more surface water reservoirs is increasingly limited by overall decreased runoff, reservoir siltation, high water losses through evaporation, and scarcity of the cost-effective and viable dam sites (Villholth and Ross, 2018).

However, mainstream approaches used for enhancing water storage are not comprehensive and often miss out the critical hydrological component of groundwater and subsurface storage. Groundwater storage, as managed natural infrastructure, could be a multipurpose, more decentralised, cost-effective and sustainable alternative to “grey” infrastructure, such as traditional-built dams (Villholth and Ross, 2018). Novel physical approaches to managing high and low flow conditions employ groundwater retention and storage during floods and subsequent recovery and use of stored water during the periods of water deficit (Van Steenbergen and Tuinhof, 2009; IWMI, 2010). Aquifers, if managed actively, provide a safe space to retain excess runoff and prevent flooding. Similarly, water stored in the aquifers can be retrived and utilised for drought mitigation based on the concept of conjunctive use. Conjunctive use has evolved to manage surface water and groundwater in a coordinated manner so as to maximize the efficient use of total water resources (De Wrachien and Fasso2002; Evans et al., 2014). Such approaches, when involving groundwater storage, oftern reffered to as managed aquifer recharge (MAR) or similar terminology, could also help reduce evaporation losses from storage, reduce the land surface imprint, support environmental objectives, and could also support natural in-situ (sub-surface) treatment of inferior water quality (Villholth and Ross, 2018). However, there is a tendency to view flood and drought risks separately, rahter than part of an integrated multi-hazard risk reduction strategy. And while, the potential role of groundwater in DRR is not adequately acknowledged and adopted at any significant scale.

Selected cases demonstrating coordinated use and management of surface and groundwater for DRR

Underground taming of floods for irrigation (UTFI)

Underground taming of floods for irrigation (UTFI) is an innovative MAR approach (Brindha and Pavelic, 2016; Pavelic, et al, 2012), following the principles described in the previous section. UTFI serves to overcome the spatial and temporal mismatch in water availability that is characteristic of recurrent flood and drought cycles (Pavelic, et al, 2018). Through targeted and managed recharge of excess wet season flows into aquifers, water security is enhanced during dry spells and droughts, making water available for irrigation. A study in the Chao Phraya Basin in Thailand shows that 28% of the coastal discharge from the basin could be harvested in one year without deleterious impacts on existing major storages, the riparian and/or coastal environment (Pavelic, et al, 2012). An economic analysis shows that the system has the potential to recover its investment within 14 years under a moderate performance scenario as well as generate around USD 250 million per year in export earnings for smallholder rainfed farmers through dry season cash cropping. A UTFI pilot testing in western Uttar Pradesh, India involving the recharging of monsoonal flows, diverted through irrigation canal system into a series of recharge wells, have shown encouraging results (Pavelic, et al, 2018). The pilot demonstrates that significant quantities of water (~70000 m^3) can be stored underground each year without detrimental impacts on the environment or groundwater quality. The groundwater buffer created through recharge can support an additional 35 hectares of dry season crop. The Government of India has formally recognised UTFI, and now included in district irrigation plans with budget allocations for scaling up beyound the pilot study.

Figure 1 a UTFI pilot testing in western Uttar Pradesh, India (photo: P. Vishwanathan)**.**

Promoting recharge condition for a climate resilient city

Enhancing recharge and subsurface water sotrage as a preparedness against climate risks and water scarcity is also practiced in urban environment. One such case is in Kumamoto, Japan where an offsetting scheme for the payment for ecosystem service (PES) was introduced since 2004 to cope with increasing groundwater demand from industries and city water supply (Shivakoti, et al, 2018). The scheme involves intentional flooding of fallow rice fields by diverting water from rivers and streams through irrigation canals. Farmers are being compensated for their work involved in harvesting water rather than crop (Taniguchi et al., 2019). A sound investigation of the hydrogeology indicating high recharge rates in the rice fields (100-200 mm/day), groundwater modelling studies, and data (quality and quantity) from observation wells were used to ascertain technical feasibility. The scientific base also helped establish a standard payment rate, based on equivalent flooded area per month (ha-month) as a unit. Farmers were paid 11,000 yen (about USD 100), 16,500 yen (USD 150) and 22,000 yen (USD 200) for flooding 1,000 m^2 rice field for one, two and three months, respectively. It was a win-win option because the farmers could get direct cash incentives, while the city and private sectors could transparently offset their groundwater footprint from abstraction. Between 2004 and 2007, the number of farming families participating in this scheme increased from 298 to 475, while the private sector also increased from one to over five in addition to the city water supply authority (Figure 2). The recharge area per month (ha-month) has more than doubled from 291 ha-month in 2004 to an estimated 636 ha-month in 2018. An estimated 163 Mm^3 was infiltrated under the recharge scheme during the past 14 years (2004-2017).

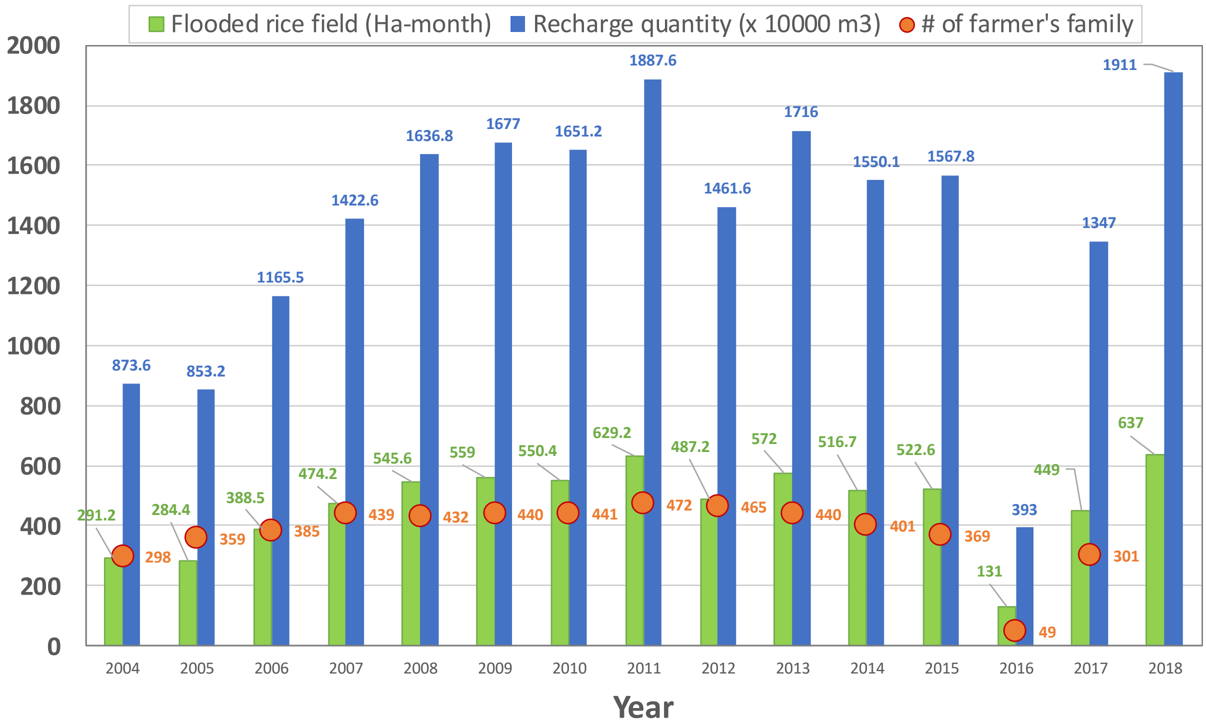

Figure 2 Development in recharge rice fields area, recharged water quantity and number of households participating in the PES system during 2004-2018. (Data for 2018 is estimated) (Source: compiled by authors based the data accessed from Water Conservation Division, Kumamoto City)

Other modalities of enhancing the groundwater buffer for cities have also be trialed with success. Metropolitan Cebu Water District (MCWD) in the Philippines has developed a MAR facility along the Managa River to store water into the aquifer as natural underground storage (Figure 3). Under the MAR scheme, water from the river is diverted to a recharge pond. The MCWD then pumps the aquifer storage for water supply to the Cebu City and surroundings.

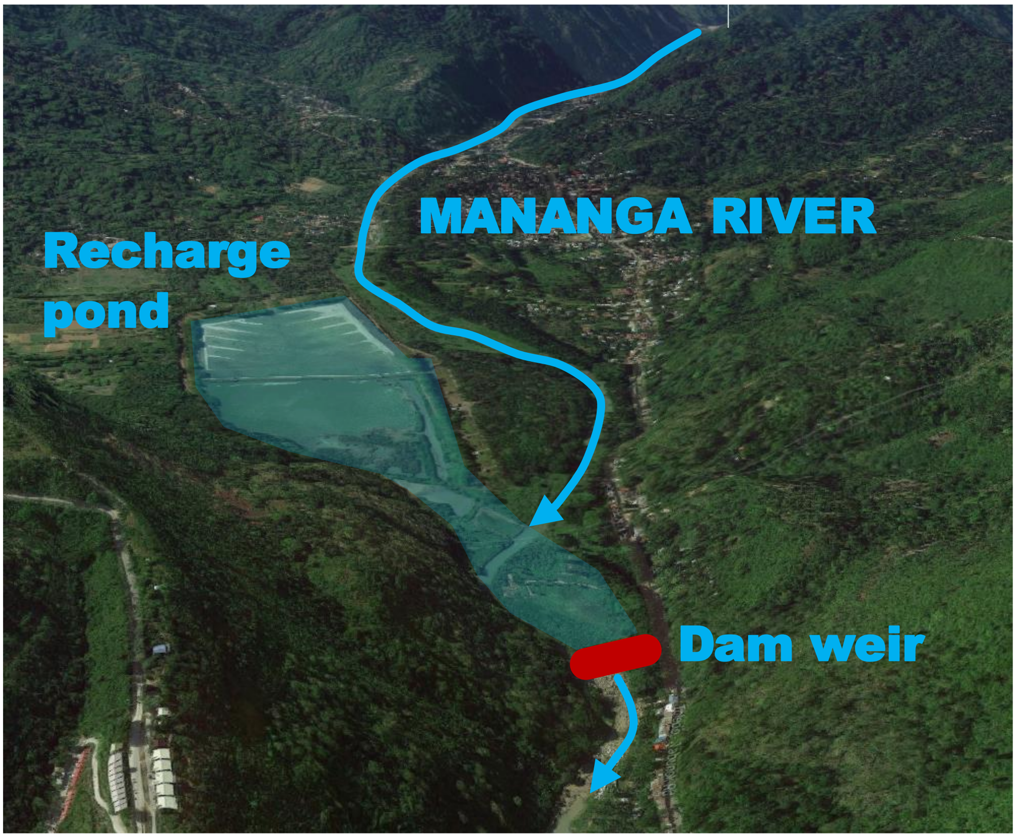

Figure 3 Aquifer recharge facility for water supply of Metropolitan Cebu Water District (MCWD), the Philippines (Source: information compiled from MCWD and Google Earth Image)

Promoting the judicious use of groundwater for climate-smart agriculture (CSA) and drought mitigation

The concept of climate-smart agriculture (CSA) has been evolving rapidly as a response to an increase in the risks associated with climate change and extreme events. CSA is an approach that calls for the integration of adaptation and the possibility of mitigation in agricultural practice in oreder to crop productivity and food security (Lipper, et al, 2018). A central idea of CSA is to increase the resilience of the farming system against local climatic variability such as sudden changes in temperature, humidity, precipitation etc. The farming communities, usually the most vulnerable smallholder farmers, are equipped to decision support tools and early warnings to enhance their farming techniques, e.g., planning of their crop calendar, selection of appropriate crops and use of water efficient cropping methods.

Groundwater is at the core of CSA due to the storage function of the subsrface. Groundwater can be used for supplemental irrigation to cushion the impacts of sudden dry spells (ACIAR, 2016; ASEAN and JICA, 2017). Groundwater irrigation is a safeguard against the risk of supply deficit from irrigation or rainfall during the crop growth period. Another functionality of the groundwater is its availability for irrigation during the dry season or droughts. Using groundwater to grow high-value crops such as vegetables and fruits during the dry season, when the lands are often left fallow, allows the farmers to capitalise on the market opportunity to sell off-season products (ACIAR, 2016). Groundwater enables higher cropping intensity and thus helps to increase the income and asset base of the smallholder farmers. Unlike canal irrigation, which is often constrained by inefficient water distribution and lower water use efficiency, farmers enjoy better control over groundwater irrigation ('when to irrigate?' and 'how much water to apply?') and minimise water losses through seepage or evapotranspiration. Since groundwater is ideal for irrigation scheduling, the farmers could easily adopt water-efficient technologies such as drip or sprinklers. To safeguard groundwater irrigation, the farmers increasingly conserve and augument it though MAR and improve soil and catchment management approaches under CSA using various technologies. Many experinaces already abound from India (Villholth and Ross, 2018). Finally, solar irrigation using solar panles to power pumping groundwater is also increasingly supporting CSA in Asia (Mukherji, 2018b). However, the intensified accessiblity to groundwater needs to be counter-balance by increase active management and concerted recharge efforts of the resource to secure sustainablity.

In semi-arid Andra Pradesh, participatory groundwater management (PGM) package was implemented by mobilising farmers water schools and community-based institutions to enhance the decision-making capacity of the farmers (Das and Burke, 2013). Farmers get understanding and hands-on experience with the groundwater irrigation system, demarcation of hydrological units, participatory hydrological monitoring, farm data management, crop–water budgeting, and artificial groundwater recharge. The role of groundwater as a tool for CSA is also being recognised across ASEAN member countries (ASEAN and JICA, 2017). In Lao PDR, a trial on community-based groundwater irrigation at Ekxang village in Phonhong district of the Vientiane plains was introduced to promote the concept of climate-resilient agriculture so that farmers could use groundwater to grow cash crops during the dry season and reduce the risk of rainfall deficit during the crop growth period (ACIAR, 2016).

Knowledge networking and regional collaboration to promote groundwater-based natural infrastructure(GBNI) solutions

Groundwater-based natural infrastructure (GBNI) solutions are at the core of the proposed strategy of integrating CCA and DRR concerns. GNBI solutions are human interventions that intentionally utilise and manage groundwater and subsurface systems and processes to increase water storage, retention, water quality and environmental functions or services for the overall benefit of water security, human resilience, and environmental sustainability (Villholth and Ross, 2018). GBNI solutions are an extension of the historical reliance on and exploitation of groundwater by intentionally enhancing and managing groundwater's natural services for multiple benefits. GBNI offers a variety of co-benefits, like water purification, conjunctive use, habitat benefits and recreation, including for DRR (floods, drought, seawater intrusion) and CCA (such as climate-resilient farming). From the cases presented in Villholth and Ross (2018), it is evident that customised GBNI solutions will be necessary to address the CCA and DRR needs of different local contexts in Asia going forward. It is essential to develop critical knowledge and capacities while generating evidence from particular settings and cases. A poor understanding and inadequate control of the processes involved with GBNI solutions could undermine the approach, leading to deterioration of already at-risk subsurface environments and services (Villholth and Ross, 2018). Knowledge networking and lesson sharing is vital to identify and showcase suitable solutions and develop model cases of GBNI for upscaling. The Groundwater Solutions Initiative for Policy and Practice (GRIPP), which is a global partnership for sustainable groundwater management comprising leading international institutions and experts dealing with groundwater research and solution implementation, has assembled a portfolio of GBNI cases illustrating outcomes and challenges that have been applied to enhance water and environmental security at the different corners the world (Villholth and Ross, 2018).

There is also a need for broader regional collaboration to bridge the gap in the science-policy interface. It may require regional partnership among scientists, researchers, government, and practitioners to facilitate adoption, upscaling, and diffusion of GBNI solutions. For that further refinement and documentation of potential technologies and practices is required as well as an assessment of the impacts of GBNI at various scales (including transboundary), including the development of assessment methodologies and indicator systems to enable benchmarking of GBNI systems in terms of disaster risk reduction, resilience, economic, environmental and social impacts.

Prerequisites and strategies for promoting groundwater-based solutions for disaster risk management and climate resilience

Above highlighted principles and cases of groundwater-based solutions demonstrates the synergistic outcomes, including for disaster risk management and climate resilience. However, depleted and polluted aquifers could cancel the prospects of beneficial groundwater uses for good and while groundwater-based solutions may partially help rectify depleted and degraded aquifer systems. Hence, already degraded systems may likely rather undermine resilience, DRR and CCA. As an example, the left side of Figure 4 illustrates that, unplanned exploitation of groundwater could result in a vicious path of depleted aquifer, resulting in increased risks of secondary impacts such as land subsidence, futher excerbating risk of flooding. There are already reports that land subsidence could increase the disaster risks from the hazards like floods and storm surge as well as seawater intrusion into aquifers across the coastal areas. Recently it was reported that Jakarta, the capital of Indonesia and a home to 10 million people, is the fastest-sinking city in the world due to the land subsidence caused by the excessive extraction of groundwater (Lin and Hidayat, 2018).

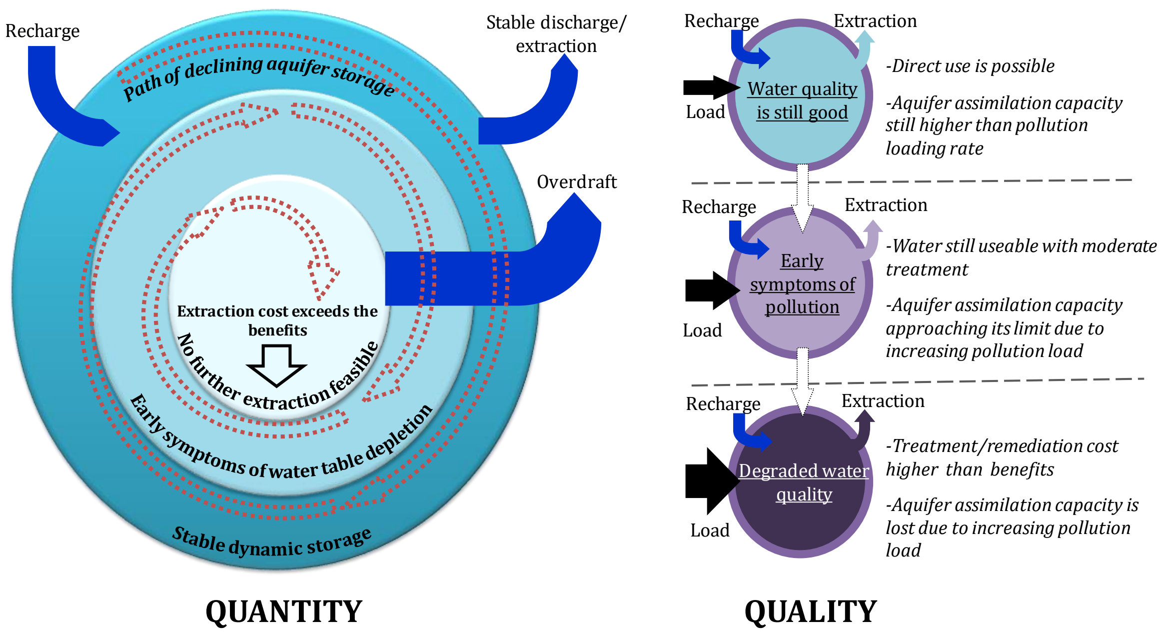

Figure 4 A conceptual model showing the path leading to declining groundwater table and degradation of water quality. The size of the arrows in the quality side indicates proportionate increase in the amount of pollutant loads. (Source: Authors).

With regards to water quality, the right side of the Figure 4 illustrates the declining natural remidiation capacity of the aquifer with increasing pollution loads could render groundwater unsafe for human uses. Without preventing such a situation, prospects of groundwater for flood and drought risk reduction can be difficult to materialise.

Proactive policies and deliberate efforts on groundwater resources development, use and protection are urgently needed not only to address the problem of groundwater depletion and pollution but also for flood and drought risk reduction. Integration of disaster risks into the framework of groundwater management could generate multiple benefits. The primary objective of the pro-disaster perspective is to recognise and safeguard groundwater storage buffers that are critical for future water security.

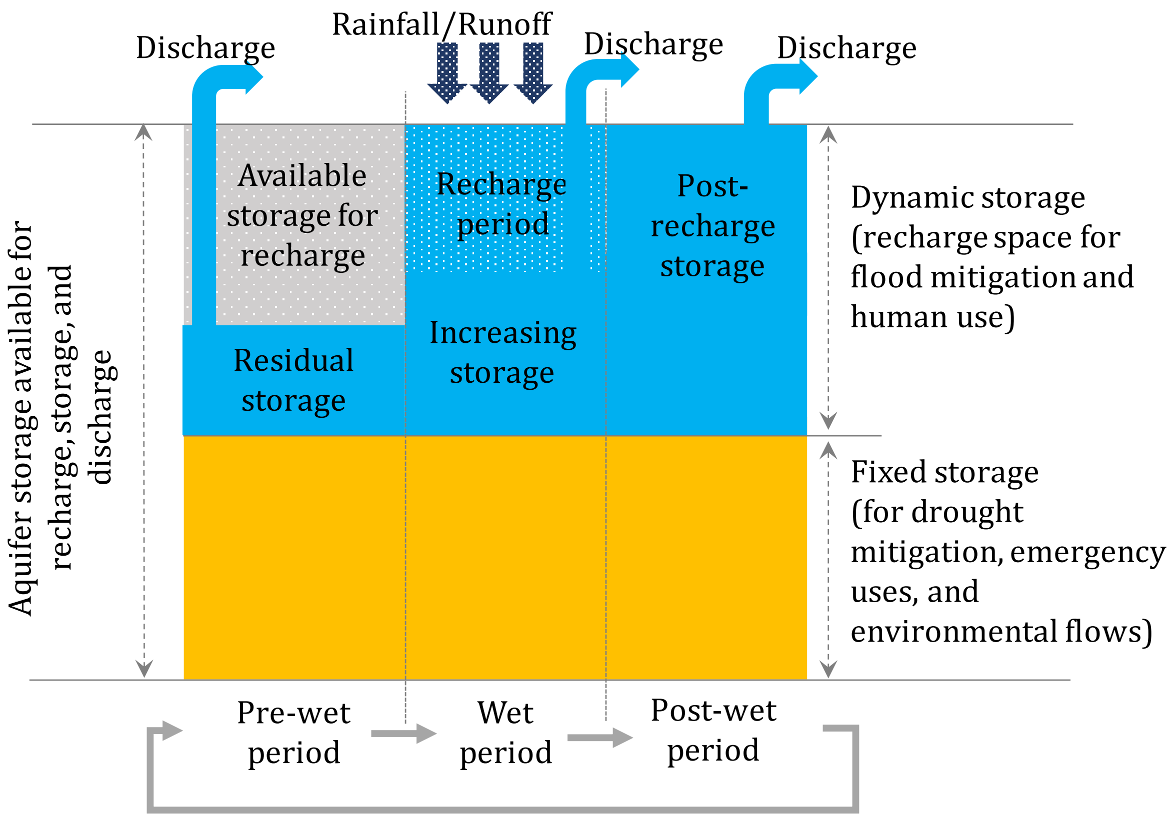

Figure 5 A depiction of simplified aquifer divided into fixed and dynamic storage to cope with wet and dry periods as well as hydrological extremes. 'Dynamic storage' refers to replenishable storage ranges controlled by natural seasonal variablity in net recharge, human abstraction, and environmental flows. 'Fixed-storage' refers to natural-storage, including deeper storage that is relatively constant and unchnaged by seasonal variablity in climate and recharge, for strategic use during emergency situations.

(Source: Authors)

In that respect, recharge, storage and discharge are three fundamental parameters to consider in support of adoption of necessary policies and legislation for integrating groundwater into DRR strategies. As shown in the conceptual Figure 5, available aquifer storage is divided into two parts: fixed and dynamic storages. The fixed storage accounts for a portion of aquifer storage, including the deepest portion, that is to ideally be maintained throughout the year. The rationale for the fixed storage is to ensure that a portion of groundwater storage is continuously available to fulfil three functions: temporary drought mitigation, emergency water supply, as well as for supporting vital environmental flows. Here, reserving a part of the storage as fixed storage represents a shift towards preparedness against groundwater droughts as well as prevention of groundwater depletion, likely from uncontroled and supply-driven groundwater resource development under prevalent practices. The dynamic storage is that portion of the aquifer, which is available for various human uses (domestic, industrial, and agricultural) and environmental flows. This portion of the storage will fluctuate depending on the rate of (natural or managed) recharge and (natural and human-induced) discharge and varies in response to external hydrological conditions during differetn times of the year. Similar to the operation of multi-purpose dams, a part of the dynamic storage could be strategically utilised before the wet season to create available storage space. Then, in the wet season, excess rainfall and runoff could be diverted and recharge into the available storage space such as through MAR. In the post-wet period, the recharged rainfall and floodwater would then ideally be available for use in the post-flooding periods.

The level of storage and groundwater uses at different periods, however, depends on several local factors such as hydrogeological characteristics, local climate and precipitation distribution, frequency and intensity of hazards (such as floods, droughts) and water demands from various sectors. There is no one-size-fits-all solution with regards to the practical implication of the proposed strategy, however, from a disaster management perspective following factors could be considered:

1. *Identification of aquifers of strategic importance and their protection*:

   As a first step, it is essential to identify the aquifers of strategic importance by undertaking resource assessment in the areas prone to flood and drought risks. The scope of resources assessment could at least cover the storage potential, recharge condition, discharges (including contribution to water ecosystems), water quality suitability and relative ease in access.

   A groundwater vulnerability maps against the hazards could be developed for the protection of resources at risk. The map could be based on datasets on bio-physical aspects (such as aquifer type(s), groundwater depth, yield, recharge, and water quality) as well as sociological, such as population density, supply coverage and access, and traditional sources (UNESCO, 2011).

2. *Setting up operational rules of balancing groundwater recharge-discharge for flood and drought risk management*

Appropriate plans and rules for enhancing recharge and storage and promote conjunctive use of surface water and groundwater are required. Fixed storage could be demarked to prevent and mitigate the drought risks and secure water supply for emergencies and ecosystem flows. Similarly, the coordinated management of surface water and groundwater would allow balancing the dynamic storage of the aquifers while satisfying the demand for water during regular periods. While this general guideline may not be applicable in all cases, such as very shallow aquifers or aquifers with prolonged recharge-discharge response, the critical aspect is to retain a certain level of groundwater storage for future (emergency) uses. Spatio-temporal monitoring of emerging climate risks, including incipient floods and droughts, is critical, so that target populations can be warned about approaching hazards, and necessary measures to protect groundwater, while also initiating specific groundwater-based soultions can be implemented with priority.

3. *Use and management of groundwater to mitigate drought impacts and secure water supply during emergencies*:

   During droughts and emergencies, the groundwater should be available equitably for all affected people such as for essential needs. A mechanism to trigger drought response will be necessary once the early symptoms of drought are apparent. An appropriate contingency plan to distribute the water during prolonged drought should also be in place. The major considerations are available storage and likely demand for water, anticipated severity and longevity of droughts or emergencies, nature of the emergency, and groundwater vulnerability to depletion and pollution. Also included are the functionality of well, pumps and related infrastructure during the crisis. Since the fixed portion of aquifer storage will be prioritised for water supply, extra care would be required on the efficient use of water resources and protection of aquifers from contamination. Compared to deep aquifer, the shallow aquifer are fastest to respond to drought as well as contamination. In such a situation, case should be given to maximize the utility of available groundwater and maintain the support for the longest duration. During floods, diverstion of flood waters towards recepting aquifers should be initiated immediately to capture water safety underground, to simultaneously mitigate flood impacts and augment supplies.

Drought and flood risk management for integrated groundwater and surface water management is part of an overall disaster risk management strategy, involving governmental activities at all levels (UNESCO, 2011). Role of the concerned government and stakeholders are crucial. The government can formulate the national drought policy by integrating all sectors and concerns of stakeholders. The government has a responsibility in terms of enacting regulations, institutional coordination, and mobilising resources to undertake resources assessment, promoting and implementing appropriate MAR system, providing training and capacity building to manage MAR system as well as conjunctive use of surface and groundwater. Similarly, active participation of stakeholders, including users, private sectors, non-government organisation, is important for preparing plans and strategies for managing groundwater for flood and drought risk reduction.

Conclusion and policy recommendations

This paper highlights a need to proactively integrate groundwater-based approaches into DRR strategies, in particular related to drought and flood hazards, in order to increase climate resilience and water security in cities and agricultural areas and for ecosystems dependent on groundwater. The paper recognises the strategic role of groundwater resources and subsurface space for the co-management of flood and drought risks and asks to prioritise the resource governance accordingly. Selected cases demonstrating the approaches to balance recharge, storage and discharge (including judicious use) aspects of groundwater resources are highlighted. Under the pro-DRR strategy, a portion of the aquifer storage is identified as fixed storage for the exclusive use for drought mitigation, emergency situation and to support vital ecosystem flows. Only the dynamic part (whether through natural or managed means) of the aquifer storage should be accessed to fulfil day-to-day demands from different sectors. Importantly, where feasible, a part of dynamic storage should be utilised for flood risk reduction by diverting and recharging excess runoff through an appropriate MAR technique. In turn, this will support drought insultation in subsequent periods.

Knowledge networking and regional collaboration are vital to facilitate, finance and create a science-policy interface required for piloting, implementing and upscaling of GBNI solutions for CCA and DRR. What is needed is to reorient current policy and legislative frameworks related to DRR for the integration of the strategic role of groundwater. Relevant policy and decision makers could adopt the following actions to facilitate the process of mainstreaming groundwater considerations into DRR management strategies and vice-versa:

- Government need to recognise and prioritise the strategic role of groundwater for drought and flood risk reduction. Integrated surface water and groundwater storage management across temporal and spatial variability of the hydrological cycle is required.
- Take steps to identify strategically located aquifers in drought and flood risk-prone areas to implement appropriate GBNI measures to enhance managed groundwater recharge and recovery for DRR, provide emergency groundwater supplies, and the long-term sustainable use of groundwater
- Integrate relevant GBNI solutions into DRR strategies and document outcomes according to emerging guidelines for most optimal upscaling of approaches.

References

ACIAR. (2016). *Groundwater for irrigation in Lao PDR: Promoting sustainable farmer-managed groundwater irrigation technologies for food security, livelihood enhancement and climate resilient agriculture*. ACIAR Policy Brief, Australia.

APWF. (2017). *Yangon Declaration: The Pathway Forward*. Yangon, Myanmar. Retrieved from http://apwf.org/apwf_wp/wp-content/uploads/2017/12/Yangon-Declaration.pdf

ASEAN and JICA. (2017). *One Against Disaster and Climate Risks: A Repository of Good Practices for Strengthening DRR and CCA Integration in ASEAN.* Bangkok, Thailand.

Brindha, K., & Pavelic, P. (2016). Identifying priority watersheds to mitigate flood and drought impacts by novel conjunctive water use management. *Environmental Earth Sciences*, *75*(5), 1–17. https://doi.org/10.1007/s12665-015-4989-z

Calow R.C., Robins N.S., MacDonald M.J., Gibbs B.R., Orpen W.R.G., Mtembezeka, P., Andrews A.J., & Appiah, S.O. (1997). Groundwater management in drought prone areas of Africa. *Water Resour Dev 3* (2): 241-261

Das, S. V. G., & Burke, J. (2013). *Smallholders and sustainable wells A Retrospect: Participatory Groundwater Management in Andhra Pradesh (India)*. Rome.

De Wrachien, D. & Fasso, C. A. (2002). Conjunctive use of surface and groundwater: overview and perspective. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, 51(1), 1-15

Evans, W. R., Evans, S. R., Holland, G. F., & Merz, S. K. (2014). *Conjunctive use and management of groundwater and surface water within existing irrigation commands: the need for a new focus on an old paradigm*.

Giordano, M. (2009). Global Groundwater? Issues and Solutions. *Annual Review of Environment and Resources*, *34*(1), 153–178. https://doi.org/10.1146/annurev.environ.030308.100251

IWMI. (2010). *Banking on groundwater in times of change*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 8p. (IWMI Water Policy Brief 32)

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.*

Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L. L. White, Eds.) (AR5 ed.). Cambridge and New York: Cambridge University Press.

Kataoka, Y. & Shivakoti, B.R. (2013). Groundwater Governance Regional Diagnosis: Asia and the Pacific region. In: *Groundwater Governance: A Global Framework for Action*. Global Environment Facility (GEF), Food and Agriculture Organisation of the United Nations (FAO), UNESCO-IHP, International Association of Hydrologists (IAH) and the World Bank, p.19

Lin, M. M., & Hidayat, R. (2018). Jakarta, the fastest-sinking city in the world. Retrieved August 15, 2018, from https://www.bbc.com/news/world-asia-44636934

Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., & Branca, G. (Eds.). (2018). *Climate Smart Agriculture* (Vol. 52). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-61194-5

Mondal, A., & Mujumdar, P. P. (2015). Return levels of hydrologic droughts under climate change. *Advances in Water Resources*, *75*, 67–79. https://doi.org/10.1016/j.advwatres.2014.11.005

Mukherji, A. (2018a). Managing energy-irrigation nexus: insights from Karnataka and Punjab states in India. Chapter 15. In: Advances in Groundwater Governance. K. G. Villholth, E. López-Gunn, K. I. Conti, A. Garrido and Jac van der Gun. CRC Press.

Mukherji, A. (2018b). Water-energy-food nexus: Are solar powered irrigation pumps the answer in South Asia? Future Earch. http://www.futureearth.org/blog/2018-jul-20/water-energy-food nexus are-solar-powered-irrigation-pumps-answer-south-asia

Mukherji, A., K.G. Villholth, B.R. Sharma & J. Wang. (2009). *Groundwater Governance in the Indo-Gangetic and Yellow River Basins: Realities and Challenges*. IAH – Selected Papers on Hydrogeology, Volume 15. CRC Press, Taylor & Francis Group. 325 pp. ISBN: 978-0-415-46580-9.

Pavelic, P., Sikka, A. K., & Villholth, K. G. (2018). *Underground Taming of Floods for Irrigation (UTFI) Controlling water-related disasters through innovative underground storage*. Sri Lanka. Retrieved from http://gripp.iwmi.org/natural-infrastructure/water-retention-3/underground-taming-of-floods-for-irrigation-utfi-2/

Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., … Smakhtin, V. (2012). Balancing-out floods and droughts: Opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand. *Journal of Hydrology*, *470–471*, 55–64. https://doi.org/10.1016/j.jhydrol.2012.08.007

Taniguchi, M., Burnett, K.M., Shimada, J., Hosono, T., Wads, C.A., & Ide, K. (2019). Recovery of lost nexus synergy via payment for environmental services in Kumamoto, Japan. *Fornt. Environ.Sci.* 7:28. doi:10.3389/fenvs.2019.0002B

Santos Pereira, L., Cordery, I., & Iacovides, I. (2009). *Coping with Water Scarcity*. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-1-4020-9579-5

Shah, T., Roy, A. D., Qureshi, A. S., & Wang, J. (2003). Sustaining Asia's groundwater boom: An overview of issues and evidence. *Natural Resources Forum*, *27*(2), 130–141. https://doi.org/10.1111/1477-8947.00048

Shivakoti, B. R. (2016). *Groundwater WASH Nexus in Asian Cities: Hanoi, Kathmandu, Khulna*. Hayama, Japan.

Shivakoti, B. R., Bengtsson, M., Zusman, E., Miyazawa, I., & Aleksiunaite, I. (2015). *Placing Water at the Core of the Sustainable Development Goals (SDGs): Why an Integrated Perspective is Needed*. Hayama, Japan.

Shivakoti, B. R., Ichikawa, T., & Villholth, K. G. (2018). *Incentivizing groundwater recharge through payment for ecosystem services (PES): Success factors of an offsetting scheme in Kumamoto, Japan*. Sri Lanka. Retrieved from http://gripp.iwmi.org/natural-infrastructure/water-storage/incentivizing-groundwater-recharge-through-payment-for-ecosystem-services-pes/

Shrestha, S., Pandey, V. P., Shivakoti, B. R., & Thatikonda, S. (2016). *Groundwater Environment in Asian Cities: Concepts, Methods and Case Studies*. *Groundwater Environment in Asian Cities: Concepts, Methods and Case Studies*. https://doi.org/10.1016/C2014-0-02217-4

Singkran, N. (2017). Flood risk management in Thailand: Shifting from a passive to a progressive paradigm. *International Journal of Disaster Risk Reduction*, *25*, 92–100. https://doi.org/10.1016/j.ijdrr.2017.08.003

Tanaka, T. (2016). Measures for groundwater security during and after the Hanshin-Awaji earthquake (1995) and the Great East Japan earthquake (2011), Japan. *Hydrogeology journal*, 24(2), 277-286.

Thirumalai, K., DiNezio, P. N., Okumura, Y., & Deser, C. (2017). Extreme temperatures in Southeast Asia caused by

El Niño and worsened by global warming. *Nature Communications*, *8*, 15531. https://doi.org/10.1038/ncomms15531

UNESCO. (2011). *Groundwater for emergency situations: a methodological guide.*

UN-WWAP. (2018). *The United Nations World Water Development Report 2018: Nature-based Solutions for Water*, United Nations Water Water Assessment Programmee (UN-WWAP), Paris, UNESCO.

Van Steenbergen, F. and Tuinhof, A. (2009). *Managing the Water Buffer for Development and Climate Change Adaptation – Groundwater Recharge, Retention, Reuse and Rainwater Storage*. Bundesanstalt füre Geowissenschaften und Rohstoffe (BGR), Cooperative Programme on Water and Climate (CPWC) and Netherlands National Committee IHP-HWRP. Waginen, The Netherlands;

Villholth, K. G., & Ross, A. (2018). *Overview on Groundwater-Based Natural Infrastructure*. Sri Lanka. Retrieved from http://gripp.iwmi.org/natural-infrastructure/overview-on-groundwater-based-natural-infrastructure/