HESS Opinions: The Myth of Groundwater Sustainability in Asia

Franklin W. Schwartz[1], Ganming Liu[2] and Zhongbo Yu[3]

[1]School of Earth Sciences, The Ohio State University, Columbus, OH, 43210, USA
5 [2]School of Earth, Environment and Society, Bowling Green State University, Bowling Green, OH 43403, USA
[3]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing, 210098, China

Correspondence to: Franklin W. Schwartz (schwartz.11@osu.edu)

Abstract. Across the arid regions of water-stressed countries of Asia, groundwater production for irrigated agriculture has led to water level declines that continue to worsen. For India, China, Pakistan, Iran and others, it is unrealistic to expect 10 groundwater sustainability in a technical sense to emerge. With business as usual, groundwater-related problems receive insufficient attention, a situation referred to as an "accelerating and invisible groundwater crisis" (Biswas et al., 2017). Another obstacle to sustainability comes from trying to manage something you do not understand. With sustainable management, there are significant burdens in needed technical and socioeconomic knowhow, in collecting necessary data, and in implementing advanced technologies. A pragmatic research agenda for groundwater sustainability should recognize that a common threat to 15 long-term sustainability could occur not just from over-pumping but widespread groundwater contamination. If groundwater sustainability is truly unachievable, then research is needed in facilitating adaption to the worst outcomes (Siegel et al., 2019). In hoping for the best outcomes, it is prudent to plan for the worst.

1 Introduction

About 20 years ago, hydrogeologists began more fully to appreciate the extent of non-sustainable withdrawals of groundwater 20 worldwide. However, recognizing a problem and doing something about it are two different things. Our focus here is Asia, where the need for sustainable groundwater management is essential, given impacts from irrigated agriculture and growing urbanization. Yet, progress towards sustainable development has been slow to non-existent. For many of these countries and even others outside of Asia, groundwater sustainability is essentially just a myth. This paper makes a case that groundwater impacts in developing Asian countries are already bad and getting worse. Further, it describes impediments to sustainable 25 groundwater management and presents suggestions for a pragmatic research agenda.

The concept of sustainability refers to the "development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable, environmental, economic or social consequences" (Alley et al., 1999). It builds on the foundational concept of safe yield as "the limit to the quantity of groundwater which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" (Lee, 1915). A modern concept of groundwater sustainability

30 recognizes the additional complexity provided by the inherent coupling of groundwater and surface water systems (Winter et al., 1998; Sophocleous, 1997) and a groundwater supply that is impaired because of contamination.

Progress toward aquifer sustainability also requires governments to provide a framework for action. The first step is developing a vision for groundwater management, which leads to policies and laws (Smith et al., 2016). The laws provide the authorities and tools needed to protect groundwater resources. Examples include explicit powers to locate and register wells, and tools to

35 manage quantities pumped through licenses or "obligations" (Smith et al., 2016). They also could extend to (i) banning new-well construction in critical areas; (ii) "capping" withdrawal rates with existing wells (Garduno and Foster, 2010); and (iii) prosecutions for illegal pumping or waste discharges (Smith et al., 2016). Legislation might also provide strict controls on the use and disposal of hazardous chemicals, or bans on the storage or use of hazardous chemicals in areas critical for groundwater. Laws and tools are ineffectual without an operational framework for managing groundwater in the field. Oversight is required

40 at national levels and with other jurisdictions that make sense, for example, states, river basins, aquifers, or local communities (Smith et al., 2016). Governments also are responsible for funding various programs, and coordinating activities with implications for groundwater in areas of surface water, agriculture, energy etc. It is also important to anticipate unintended consequences from actions taken in other parts of the government, a theme we will return to.

Successful implementation of management programs depends on the support and willing participation of local stakeholders.

45 When stakeholder views are represented, especially during the drafting of legislation and implementation, there is broader compliance with regulations, a willingness to collect and share basic groundwater data, and active self-regulation (Smith et al., 2016; Garduno and Foster, 2010).

Governments can apply socioeconomic tools to promote groundwater sustainability. For example, charging for the water will reduce its use, especially with large commercial users (Garduno and Foster, 2010). Of course, this step requires the difficult

50 task of metering of water used in irrigation. A second example is strategic, governmental investment to provide for efficient irrigation. Another beneficial direction is reversing common macro-policies that actually promote groundwater over-use (Garduno and Foster, 2010). Examples in India include price support for crops that need lots of water, and reduced or no costs for agricultural necessities, such as rural electric power and agrochemicals.

Asia, basically, should be far along towards groundwater sustainability. Earlier studies pointed out problems and posited

55 solutions. For example, in 2000, the World Bank formed the Groundwater Management Advisory Team (GW-MATE). Over the next decade, team members worked in Asia and elsewhere on groundwater-related issues and sustainable groundwater use. Their reports identified seriously impacted groundwater systems and provided practical approaches towards sustainability.

2 Trends in Depletion and Contamination of Groundwater Continue to Worsen

60 In China, India, Pakistan and other hotspots (Figure 1), the impacts to groundwater due depletion and contamination are continuing to worsen for reasons that we will discuss in Section 3. China's most visible groundwater problem is associated with the over-production of groundwater from aquifers underlying the core of the North China Plain (Figure 2a). Groundwater

withdrawals since 1960 have produced excessive drawdowns that began to receive attention about 15 years ago. Water-level declines of > 20 m were evident in the shallow unconfined aquifer and > 40 m in the deep freshwater aquifer (Foster and Garduno, 2004). Estimated reductions in groundwater storage were of the order of -8.8 km^3 yr^{-1}. By about 2010, drawdowns as high as ~60 m were reported in the unconfined aquifer (Cao et al., 2012) and >80 m in the deep freshwater aquifer (Zheng et al., 2010) (Figure 2a).

The aquifers of the North China Plains are essential to wheat production, to maintaining socio-economic contributions associated with the agricultural economy, and in supplying water to cities (e.g., Beijing and Baoding) (Foster and Garduno, 2012). However, continuing water-level declines indicate limited progress towards sustainability. A recent assessment using GRACE (Feng et al., 2018) indicates almost constant declines in storage of -7.2 km^3 yr^{-1} from 2002 to 2015. This result compares to an earlier estimate of -11.3 Gt yr^{-1} (-11.3 km^3 yr^{-1}) (Rodell et al., 2018).These impacts will continue even with water available from the South to North Water Transfer (Ye et al., 2015; Bloomberg, 2017).

In China, there are other places with groundwater-related problems. Depletion is evident at some 164 locations, encompassing ¾ of China's provinces (Wang et al., 2018). Declining water levels have increased the size of the area affected by land subsidence – 4.9x10^4 km^{2}in the 1990s → 7.9x10^4 km^2 in 2000s → 9x10^4 km^2 in 2012 (Wang et al., 2018). Pumping of groundwater in coastal areas is also producing seawater intrusion.

The groundwater situation is also troubling in India with an annual production of ~250 km^3, the largest in the world. For India, groundwater provides 85% of drinking water and 60% of water for irrigation (World Bank, 2010). There two prototypical settings for groundwater in India. Shallow hard-rock aquifers, like the Deccan Traps (Basaltic Lava Flows) or weathered granitic rocks, occur across the upland areas of the Indian Peninsula (Figure 2b). These low yielding, weathered bedrock aquifers are important sources of water, which are being increasingly exploited with rates of withdrawal often greater than recharge (World Bank, 2010). Water typically occurs in fractures in the upper 25 m. During a typical year, increases in water levels due to recharge from monsoonal rains do not fully recover from the withdrawals of previous years.

The Indo-Gangetic alluvial (IGA) aquifer system occurs across the top of India (Figure 2b), extending into Pakistan, Nepal, and Bangladesh. It includes flood plains along the Indus and Ganges Rivers and their tributaries as a thick sequence of alluvial sediments derived from the Himalayan Mountains (MacDonald et al., 2016).

Groundwater production from the IGA aquifer system in 2010 (including adjacent countries) was 205 km^3 yr^{-1}, increasing at 2-5 km^3 yr^{-1} due to continued expansion of irrigated agriculture (MacDonald et al., 2016). These large withdrawals are offset by comparably large inflows as leakage from irrigation canals, irrigation return flows, and natural recharge from monsoonal rains. Assessments are complicated by spatial variability in hydraulic parameters, various water quality impacts, and uncertainties in recharge estimates (MacDonald et al., 2016). Rates of storage depletion, estimated using GRACE data, range from 17.76 ±4.5 km^3 yr^{-1} (Rodell et al., 2009) to 14 ±0.4 km^3 yr^{-1} (Long et al., 2016). The most realistic estimate (2000-2012) is somewhat lower, 8.0 ±3.0 km^3 yr^{-1} (5.2 ±1.9 km^3 yr^{-1} for northern India), based on actual groundwater measurements (MacDonald et al., 2016).

Yet, impacts from pumping are not the urgent problem that some measurements (e.g., Rodell et al., 2009) imply. The relatively large quantities of groundwater stored in the upper 200 m of the IGA system coupled with 100 plus years of additional recharge from unintended canal leakage and irrigation return flows means that depletion is restricted to certain regions. Yet, what is concerning is that the greatest recent water-level declines are evident in northern Indian and Pakistan, areas essential for food production with irrigation.

What is often misunderstood about IGA aquifer system is the greater threat to groundwater sustainability associated with water quality issues – salinity, urban and industrial contaminants, and arsenic in groundwater (MacDonald et al., 2016; Foster et al., 2018; Young et al, 2019). The origin of salinity in the shallow groundwater is complex but commonly associated with effects of irrigation. Leaking canals, over more than a century in some instances, have led to waterlogging and salt accumulation in soil, and the salinization of recharge (Foster et al., 2018). Large capacity irrigation wells are also capable of mobilizing naturally salty water occurring at depth with up-coning. Estimates are that 18,000 km^3 or 60% of shallow groundwater in the IGA system suffers water-quality impairment (MacDonald et al., 2016).

The largest cities of India exemplify the emerging problems of water sustainability. A useful example is Delhi whose population of ~25 million is poised to double in the next 30 to 50 years. Most of Delhi's drinking water comes from surface-water sources; but groundwater from the IGA aquifer system is both important and problematic. Almost every sustainability issue just discussed is a major problem for Delhi – rapidly declining water levels, salinity at depth, and nitrate concentrations commonly >45 mg/L and as high as 1500 mg/L. Various news outlets have been active in expressing concerns about the local impacts of these problems (Text Box 1).

Political and policy failures associated with groundwater and surface water have created a crisis for India that bears directly on food, water and health (Biswas et al., 2018). Citing centuries of mismanagement of water resources, and "institutional incompetence" (Biswas et al., 2018) in the context of a large growing population, there has been no willingness for action politically in India beyond "cosmetic changes" (Biswas et al., 2018). Although issues involved with surface waters (contamination, fights over allocation, and reliability of public supplies) are worsening; "the groundwater situation is even worse" (Biswas et al., 2018). Yet, data on groundwater is poor in quality or unavailable. Rampant growth in groundwater utilization is linked in part to the failure of government to provide surface water for irrigation (Biswas et al., 2018).

Pakistan is another country with groundwater issues threatening future sustainability. Its large population, ~208 million and growing, contributes to its water scarce status with a per capita availability of water in the lowest 10% of the world's population (Young et al., 2019). The Indus River and its tributaries are significant surface-water resources, used almost entirely to support irrigated agriculture. Yet, the use of water is inefficient with significant losses due to canal leakage, evaporation, and over-irrigation (Young et al., 2019).

The IGA aquifer system extends southward into Pakistan along the length of the Indus River. For now, levels of groundwater in the IGA aquifer system in Pakistan are stable or even increasing (MacDonald et al., 2016). The main problems are associated with water-level declines of ~10 m since the 1980s in the important food growing area of Punjab Province to the northeast (Young et al., 2019). Here, as in India, canal leakage and irrigation return flow have continued to provide an unmanaged

130 aquifer recharge system that has banked water in the subsurface since the late 1800s to the point of waterlogging in some places (MacDonald et al., 2016). The greater threat to sustainability comes from the kinds of water quality problems mentioned previously.

There is little progress in the development of a sustainability ethic for groundwater management in Pakistan. Assessments are frustrated by an absence of data and the lack of a quantitative understanding of groundwater-surface water interactions along
135 the major rivers (Young et al., 2019).

Elsewhere in Asia, the non-sustainable production of groundwater has resulted in even more serious problems. In Iran, the significant loss of groundwater resources could render major parts of the country uninhabitable with the possibility of millions displaced as conditions worsen (Collins, 2017). In addition to widespread declines in water levels, there are significant problems related to land subsidence and declining water quality (Madani et al., 2016).

140 Various factors have contributed to groundwater insecurity. Iran has a growing population of ~80 million, which has doubled over the last 40 years (Bozorgmehr, 2014). The country is dry, making groundwater a growing source for drinking and irrigation water. A continuing trend towards urbanization has resulted in an urban population of 70% with 18% in Tehran (Madani et al., 2016). Since 1999, there has been a succession of drought years. When coupled with an increase in annual temperature, the new normal is dryer and hotter weather with a likely decline in precipitation and recharge in coming decades
145 due to climate change (Gohari et al., 2013; Nabavi, 2018).

This water crisis is also driven by socioeconomic decisions in the late 1970s to become self-sufficient in wheat, the country's most important crop (Collins, 2017). The expansion in wheat production through irrigation has had significant impacts on groundwater. Yet, there are few signs of movement towards a more sustainable groundwater future (Collins, 2014).

Another Asian hot spot for impacts associated with unsustainable groundwater production is Jakarta, Indonesia, on the island
150 of Java. Approximately 25-30% of the more affluent residents of this large city receive piped-in surface water (Colbran, 2009). Others obtain drinking water from large numbers of groundwater wells, rainwater, vendors, bottled water, etc. The poor quality of piped water has pushed industries and other large consumers toward the utilization of deep (~150 m) groundwater (Colbran, 2009).

Yet, this is not a drought story. Large, localized production from the shallow unconfined aquifer ~50 m thick and a deeper
155 confined aquifer ~100 m thick is not sustainable even with significant natural recharge (Kagabu et al., 2013). The overuse of groundwater has been evident for a long time. For example, in 1995, reported pumping rates were three times larger than recharge rates. By 2008, drawdowns in the deep aquifer were >40 m with hydraulic heads 25 m below sea level (Kagabu et al., 2013). Water quality in the shallow aquifer is impacted by urban contaminants, like NO_3 (Kagabu et al., 2013) because there are virtually no sanitary sewer systems. There is evident seawater intrusion landward within the deep aquifer caused by
160 over-pumping. Declining water levels have also resulted in subsidence that in several places exceeds 2 m (IRIDeS, 2017). Now approximately 40% of the city's land surface is below sea level with only a seawall to protect land from inundation. Yet, as far as groundwater utilization, it appears to be business as usual.

3 What are the Hurdles to Groundwater Sustainability?

165 Developing Asian countries have encountered significant roadblocks hindering progress towards groundwater sustainability. So far, it has been relatively painless for countries and large cities simply to ignore groundwater issues, which in the case of India has been called an "invisible" crisis (Biswas et al., 2017). Of greater concern in Asian countries is a collection of more critical national issues related, for example, to growing their economies, feeding their people, maintaining national security, and improving the social conditions for growing populations.

170 In Asian countries, there much less deference to water security than food security. India's "Green Revolution" (GR) is a case in point. In the 1950s, government leaders in India were troubled by the deaths from the Bengal Famine of 1943 (Rahman, 2015). With their growing population, achieving food security became a top priority. In the 1960s, the GR began with an expansion in agricultural lands, new high-yielding seeds, expanded irrigation, double cropping, and vastly increased fertilizer and pesticide applications (Rahman, 2015; Schmanski, 2008). India became food secure with large increases in the production

175 of food and cereal grains.

Yet there is dark side, which includes severe social, economic, and environmental problems, particularly in the amazingly productive Punjab region of India (Figure 2b). Examples include the high suicide rates of farmers, increasing cancer rates from pesticides, and especially the unsustainable utilization of groundwater (Schumanski, 2008; Singh and Park, 2018). Groundwater impacts were slow to develop but are now serious with water-level declines ranging from 4.5 m to 35 m (Rahman,

180 2015).

China, India, and Iran have been able to aggressively ramp up agricultural production to feed their people without adequately planning for the impacts to groundwater. With recharge and the inherent capacity of large aquifers to store abundant groundwater, groundwater problems developed incrementally and have been difficult to recognize in data-poor settings. Now, food production from irrigated agriculture is structurally part of the national economies of these countries, making it difficult

185 to reduce the production of food and groundwater.

The second major impediment to sustainable management is limitations in terms of a socioeconomic framework for action and necessary data. Following here is a discussion of these issues for three large countries India, Pakistan, and China.

As mentioned, centralized groundwater management requires appropriate policies, legislation, and a functional regulatory framework. India has a useful collection of laws in place but groundwater management is "weak to nonexistent" (World Bank,

190 2010). The most important limitation is that water is a state responsibility and many of the states in India have no capacity to monitor production or enforce regulations, especially with many small water users. Thus, India's estimated 20 million wells are unregulated and outside any regulatory framework (World Bank, 2010).

Another drag on sustainability efforts in India is political sensitivities. For example, the free or nearly free electrical power for irrigation in rural areas is a significant factor in groundwater over-pumping. Yet, there is no political will to change this policy

195 (World Bank, 2010). It is also problematic that groundwater oversight exists in many government agencies with no clear

definition of responsibilities between the state and central governments. Thus, for India, there are no realistic possibilities for state intervention in groundwater management (World Bank, 2010). The only opportunities exist at the community level.

The situation in Pakistan is quite similar to India with little prospect for progress. Within their federal system of governance, provinces have responsibilities for managing groundwater. However, there are neither provincial regulatory frameworks nor

200   capacity to regulate access to groundwater (Young et al., 2019). There is limited technical capabilities in managing surface-water and groundwater conjunctively (Young et al., 2019). Thus, the long-term risk to groundwater sustainability in the Lower Indus River basin and delta from inefficient irrigation and seawater intrusion are unmitigated.

In China, there are legal/operational frameworks that have the potential to contribute to groundwater sustainability. A complex, multi-tiered system for water-resource administration exists, with units represented all the way down to local Water User

205   Associations (Doczi et al., 2014). Most progress in the management of agricultural water has been with traditional surface-water irrigation systems, which has contributed to rises in production and irrigation efficiency (Doczi et al., 2014). Groundwater is more problematic with declines continuing (Doczi et al., 2014; Biswas and Hartley, 2017; Wang et al., 2018). The number of privately owned wells has increased significantly giving farmers the ability to "protect their crops" (Doczi et al., 2014) from drought and the inconsistent availability of surface water for irrigation.

210   Doczi et al. (2014) point to problems in implementing national policies with regulation unable to catch up with the rapidly expanding use of groundwater. Specific measures like drilling permits, quotas on water, and fees have been implemented but neither broadly (Wang, et al., 2018) nor effectively (Doczi et al., 2014). Controlling water-level declines across the North China Plain is also complicated by the growing need for groundwater to help support rapid urban and industrial growth (Biswas and Hartley, 2017). However, China does have the fiscal and technical capacity to support projects focused on sustainability.

215   The challenge in this respect is in finding water sources for MAR.

The Asian countries we have examined also have data problems. Some water-level data are available in areas most impacted by over-pumping. However, information on what wells are pumping what quantities of water typically do not exist. It is evident that the tens-of-millions of wells in both China and India provide a formidable operational challenge in monitoring. With the pervasive irrigation associated with rivers and systems of canals, unmanaged aquifer recharge is a significant, yet unknown

220   factor influencing water levels. There is even less information on threats to sustainability coming from groundwater contamination.

Development of some "understanding" in relation to the sustainable management of groundwater depends upon programs of hydrogeologic mapping, monitoring, and modeling. Yet, there is little discernable progress in data collection necessary to support sustainability initiatives in either India (Biswas et al., 2017) or Pakistan (Young et al., 2019). There may be somewhat

225   more progress in China but information there is siloed and lacking in necessary transparency.

There are notable activities underway, which contribute to groundwater sustainability by promoting groundwater recharge and storage. Yet, just what that contribution actually is unknown in a technical sense. For example, India is the world leader in the number of installed systems to store water in the subsurface. (Dillon et al., 2019). There are several million traditional (often old) recharge structures, such as, percolation tanks/ponds and streamed infiltration systems with millions more planned

230   (Dillon et al., 2019). Yet, there are few quantitative assessments of how well these systems work in promoting recharge (Dillon et al., 2019; Dashora et al., 2018).

China, however, has a much smaller number of these kinds of traditional recharge projects in operation (Dillon et al., 2019). Instead, they are investing in their "sponge-city" concept, a collection of "low-impact" practices (Biswas and Hartley, 2017) designed primarily to reduce urban flooding and water pollution. The idea is to store water in the subsurface through pervious

235   pavements or utilizing/storing storm water in rain gardens or rooftop gardens. These kinds of green infrastructure are developing in China. While contributing to groundwater sustainability through urban recharge, it is not clear what that contribution will be.

In the megacities, like Jakarta, Delhi, and Karachi, our reviews found the status of groundwater data to be meagre to nonexistent, very inadequate to support technical or socioeconomic efforts towards sustainability.

240   The kinds of technical knowledge and data needed for sustainable groundwater management are well known. They include a robust qualitative and quantitative understanding of how the land-based portion of the hydrologic system functions, physically, chemically and biologically. Basic data collection involves metering or other approaches to establish water-utilization, groundwater/surface-water interactions, aquifer characterizations, testing, sampling and measurements in the field, supported by various monitoring networks, data acquisition systems, laboratories and database systems. Figure 3 highlights the broad

245   scope of data needs with an illustrative conceptual model of a complex coastal hydrologic system (CDWR, 2016).

Asian countries starting from scratch will need to anticipate costs associated with years of field operations in, for example, groundwater mapping, aquifer testing, and water quality measurements. Various monitoring networks will need to be designed and emplaced, as well as equipment to be purchased, installed, and operated. Provision must be made for data compilation and storage, interpretations, modeling, laboratory measurements, etc. What adds even more difficulty is an absolute need to monitor

250   for one to several decades to provide an average set of baseline conditions (CDWR, 2016). The creation of conceptual models, water balance calculations, and compliance assurance all require these kinds of data. A useful place to gain perspective is with a series of best practices reports of the California Department of Water Resources (e.g., CDWR, 2016). They are intended to provide technical assistance for California's new state-wide initiative in sustainable groundwater management.

The third major obstacle is that technically-oriented sustainability initiatives require expensive infrastructure with continuing

255   operating costs. Consider a problem where the key issue with sustainable management is water-level declines from excessive pumping. The operational objective is to end up with an aquifer system where water storage does not change over the long-term while maintaining appropriate natural discharges to rivers and springs. Reductions in storage due to unsustainable production can only be reversed in two ways – increasing the quantity of inflows to the aquifer (e.g., recharge) or decreasing the outflows (e.g., pumping with wells). The yellow box in Text Box 2 lists four recharge schemes to increase inflows to

260   aquifers (i.e., MAR) with links to the associated issues/problems, as indicated by the red arrows.

Clogging is a significant problem reducing the quantities of water infiltrated or injected into the subsurface. Consequently, MAR systems require regular maintenance to maintain performance. In an Asian context, the other issues affecting MAR (Text Box 2) also provide formidable challenges. Finding water to recharge an aquifer can be difficult. Surface water can be scarce

because excess water is often only available with summer monsoons. Treated municipal sewage, another important source of water, is often not available or of appropriate quality. For example, ~50% of Delhi's population has no sewers (Sengupta, 2015) with significant quantities of wastewater dumped into the nearby Yamuna River or left to seep into the ground. In addition, there tends to be declining interest in projects involving long transfers of water. Farmers in India (and China) prefer government-supplied surface water for irrigation is a preferable alternative to groundwater sources (World Bank, 2010). Infrastructure, like reservoirs, pipelines or canals is needed to transfer water to where it is needed.

A variety of strategies exists to reduce groundwater withdrawals. Replacing groundwater (i, ii green, Textbox 2) in irrigation with imported surface water or treated wastewater is often not practicable, as was mentioned. Decreasing agricultural production through acreage reductions, growing one crop per year instead of two, or changing to crops that use less water will lead to less groundwater utilization (iii to vi, Text Box 2). Yet, on the one hand, with governments firmly committed to food security and poor farmers needing to maintain their livelihoods, such initiatives are unattractive. On the other hand, these strategies require minimal technical expertise. Governments can pass a law, check the sustainability box, and plan to spend money to import some food. Finally, more efficient irrigation technologies might lead reduced pumping (Garduno and Foster, 2010)

The feasibility of sustainable groundwater management is on display with projects of Orange County Water District (OCWD) in southern California. This case study illustrates that in arid areas with modest recharge and significant withdrawals, groundwater sustainability will require MAR. It also shows how wastewater recycling can provide a source of water when there are limited prospects for new surface-water. However, this source is expensive, in terms of infrastructure and advanced technologies for purification. OCWD distributes water to ~2.4 million people. Sustainable operation of the aquifer systems produces ~345 Mm^3 $yr^{-1}$of groundwater, which is ~4.7 times the natural recharge of 74 Mm^3 yr^{-1} (Hendron and Markus, 2014). MAR, using infiltration basins, makes up the deficit, with185 Mm^3 yr^{-1} coming from the Santa Ana River and 86 Mm^3 yr^{-1} from purified urban wastewater (Hendron and Markus, 2014). Municipal wastewater collected, treated, with additional advanced treatment with reverse osmosis and more. Some of this purified water is used to maintain a hydraulic barrier in the subsurface to prevent sea-water intrusion. This kind of system, providing evidence-based sustainability and high quality water, is expensive to build and operate. It is also critically dependent on monitoring (OCWD, 2015).

Such sophisticated water management systems are uncommon in Asia. Yet there are several extraordinary examples. The island state of Singapore is home for an innovate collection of management activities creating near self-sufficiency from water imports from Malaysia (Irvine et al., 2014). Drinking and industrial waters come from capturing and treating rainwater captured with urban catchments, the advanced purification of urban wastewater to a product called NEWater, and the addition of desalination plants (Irvine et al., 2014). MAR projects in Israel also provide useful examples. The Dan Region Reclamation Project (also known as Shafdan) uses treated wastewaters from Tel-Aviv and environs for MAR (Cikurel et al., 2012). The system yields 140 Mm^3/yr of high quality water that is pumped 100 km south for irrigation. As of 2012, this was the largest project of its kind in Europe and the Middle East (Cickurel et al., 2012). Israel also depends on the reverse osmosis of seawater with periodic storage of excess water in the Israeli Coastal Aquifer (Ganot et al., 2018).

The common characteristics of all three of these successful implementations include (i) extreme shortages of water to the point of exhausting local surface water and groundwater supplies, (ii) technologically advanced and prosperous societies, with 300 modern and reliable infrastructures, and (iii) a manageable problem scope stemming from relatively small populations.

4 Planning for the Worst and Hoping for the Best: Groundwater Research Directions

There are compelling arguments why it is unrealistic to expect groundwater to be managed sustainability in developing Asian countries. Progress towards groundwater sustainability in Pakistan, India and China is being frustrated by the general inability 305 to bring traditional socio-economic tools to bear towards reducing groundwater demands. The indictment for India, "centuries of mismanagement, political and institutional incompetence; indifference at central, state, and municipal levels, and steadily increasing population" (Biswas et al., 2017) applies as well to other countries. For India and Pakistan where operational management is at the level of states and provinces, there is no capacity to regulate. For the most populous countries, China and India, the tremendous numbers of groundwater users large and small confound regulation of groundwater. Thus, 310 groundwater that has always been freely available for irrigators remains so.

Groundwater-related problems are largely invisible (Biswas et al., 2017) and seemingly irrelevant to a greater agenda. For China, India, Pakistan and Iran, there is an undeniable focus on food production to support growing populations and changing food preferences of increasingly affluent societies (Young et al., 2019). The continuing trend towards urbanization at all scales up to megacities is localizing water demands and exacerbating groundwater problems. The existence of necessary data as a 315 prerequisite for problem understanding and management decisions remains a problem for all countries except perhaps China. With time, however, satellite-remote sensing, particularly GRACE (Feng et al., 2018; Long et al., 2017; Rodell et al., 2009; Rodell et al., 2018), may play a larger role with evidence-based groundwater sustainability analyses. However, field-based hydrogeological campaigns (e.g., MacDonald et al., 2016) and comprehensive monitoring are essential for understanding how these complex systems work.

320 Finally, we touch on the state of research in these countries associated with groundwater sustainability. With China as an obvious exception, groundwater-related research is not close to where it needs to be. Our review is evidently cursory, focused mainly on available information in journal papers and government reports. Much of what is known about the groundwater in Asian countries (China again excepted) comes from external researchers but with in-country collaborators and cooperators. Influential in this respect are long-term studies by The World Bank, large-scale interpretations of water storage changes with 325 GRACE, and a few regional groundwater investigations. One area of critical need is research to address water quality issues in both India and Pakistan. Work by MacDonald et al. (2016) and Foster et al. (2018) has identified the threat to sustainability related to problems of salinity and groundwater contamination. For example, with IGA aquifer system, this threat around issues of water quality is more serious than over-pumping (MacDonald et al., 2016). Problems of arsenic pollution are widespread including Pakistan (ref), while human activities that have led to groundwater salinization and urban/agricultural contamination

330 (MacDonald et al., 2016). There are also hints of broad groundwater contamination in China (Biswas and Hartley, 2017), although information is scarce.

Adding water-quality issues to the sustainability mix reveals even greater deficiencies in data and needs for research across the board modeling and arid-zone geochemistry. Salinity problems are complicated because impacts can occur in so many ways. In Pakistan, saline water exists at depth in addition to salinized recharge caused by waterlogging. Moreover, this deep

335 groundwater water can be remobilized by pumping (Foster et al., 2018). In China, shallow groundwater across the eastern half of the North China Plain is salinized (Foster and Garduno, 2004). This creates the possibility for eventual water quality impairment in the underlying deep freshwater aquifer as over-pumping there continues.

We hope that countries in Asia begin to address sustainability problems in critical areas more aggressively along with the practical hydrogeologic investigations needed to support needed projects. Yet, there is a significant risk that neither will happen

340 given the problems of capacity and socio-economic constraints that we discussed. An immense transition will be required to move from water policies, viewed widely as muddling along from one crisis to the next without little substantive action to full-blown projects with demonstrated compliance (i.e., Singapore, California). Moreover, it remains to be seen whether the successful strategies in places with relatively small and economically advantaged populations are practically scalable to many tens-of-millions of people in developing countries. In any case, logistical constraints mean that it will be decades before

345 sustainable systems are up and running. Such a delay increases the possibilities of predictable surprises – the problems (e.g., climate change) that are anticipated but ignored (Bazerman and Watkins, 2004).

There are basic technical approaches that can contribute to sustainability without the certainty of knowing long-term outcomes. For example, several countries are invested in recharge projects, India with their tradition MAR (Davis et al., 2018) and China with their "sponge city" concepts. Yet, these approaches are no panacea. For example, tradition approaches to water harvesting

350 in India are not well suited for hard-rock areas, impact downstream users, and often lead to more pumping (World Bank, 2010). All these technologies would benefit from analyses to identify strengths and weaknesses and to optimize the benefits for groundwater sustainability. Studies sponsored by the World Bank (2010) suggest that there is hope for community-based management in the hard-rock areas of India and perhaps elsewhere.

There are risks that that Iran, India and Pakistan will run short of groundwater in places from over-pumping and be adversely

355 affected by global climate change, especially floods and droughts. The dimensions of these risks are not well defined. Yet, in the case of climate change, a forward-looking study has looked potential threat in order that countries "can plan and prepare" (Rigaud et al., 2018). It involved modeling future in-country migration in arid regions of the world due to climate change. The results for South Asia suggested that by 2050, there could be 35.7 million in-country climate migrants under a pessimistic future climate scenario. In the context of groundwater sustainability, we envision a need for similar scoping studies to examine

360 this threat. No doubt, such analyses would be difficult and uncertain with the broad absence of data. Yet, with potentially 100s-of-millions of people at risk it would be prudent to evaluate the worst outcomes while hoping for the best.

Data availability. The production of the digital elevation maps for Figure 2 used the following data sources:

SRTM 90m DEM Version 4, Accessed and download from: http://srtm.csi.cgiar.org/srtmdata/

365 GIS data for administrative area boundaries from: https://www.diva-gis.org/gdata

Country boundaries: https://www.naturalearthdata.com/downloads/50m-cultural-vectors/

(Last access for all 15 May 2019)

Author contributions. FS conceived the idea and wrote much of the manuscript. GL created the colored, three dimensional

370 elevation maps for China and India and prepared Figs. 1 and 2. Both GL and ZY contributed to the paper, especially insights and material with respect to China. All authors reviewed early manuscript drafts and the final draft.

Competing interests.

The authors declare that they have no conflict of interest.

375 **References**

Alley, W.M., Reilly, T.E., and Franke, O.L.: Sustainability of Ground-Water Resources, U.S. Geological Survey, Circular 1186, 79 pp. (available online: http://pubs.usgs.gov/circ/1999/circ1186/pdf/circ1186.pdf), 1999.

Biswas, A.K. and Hartley, K.: China's groundwater crisis, Asia & the Pacific Policy Society Policy Forum (available online: https://www.policyforum.net/chinas-groundwater-crisis/), 2017.

380 Biswas, A., Tortajada, C., and Saklani, U.: Pumped dry: India's invisible and accelerating groundwater crisis, Asia & the Pacific Policy Society Policy Forum (available online: https://www.policyforum.net/pumped-dry/), 2017.

Bozorgmehr, N.: Iran: Dried out, Financial Times (available online: http://www.ft.com/content/5a5579c6-0205-11e4-ab5b-00144feab7de), 2014

CDWR (California Department of Water Resources): Best Management Practices for the Sustainable Management of

385 Groundwater Water Budget, California Department of Water Resources, 51 pp. (available online: http://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Sustainable-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents/Files/BMP-4-Water-Budget.pdf), 2016

Bloomberg: World's Largest Water Diversion Plan Won't Quench China's Thirst. (available online: http://www.bloomberg.com/news/articles/2017-12-10/world-s-largest-water-diversion-plan-won-t-slake-china-s-thirst),

390 2017.

Cao, G., Zheng, C., Scanlon, B.R., Liu, J., and Li, W.: Use of flow modeling to assess sustainability of groundwater resources in the North China Plain, Water Resources Research, 49, 159-175, 2013.

Colbran, N.: Will Jakarta Be the Next Atlantis? Excessive Groundwater Use Resulting from a Failing Piped Water Network, Law Environment and Development Journal, 5, 20-37, 2009.

395 Collins, G.: Iran's Looming Water Bankruptcy, Rice University's Baker Institute for Public Policy, 19 pp., 2017.

Dashora, Y. et al.: A simple method using farmers' measurements applied to estimate check dam recharge in Rajasthan, India, Sustainable Water Resources Management, 4, 301-316, 2018.

Dillon, P. et al.: Sixty years of global progress in managed aquifer recharge, Hydrogeology Journal, 27, 1-30, 2018.

Feng, W., Shum, C.K., Zhong, M., Pan, Y.: Groundwater Storage Changes in China from Satellite Gravity: An Overview, Remote Sensing, 10, 674-698, 2018.

Doczi, J., Calow, R., and d'Alancon, V.: Growing more with less: China's progress in water management and reallocation, Case Report, Overseas Development, Development Progress, 47 pp. (available online: https://www.odi.org/publications/8796-growing-more-less-china-s-progress-agricultural-water-management-and-reallocation), 2014.

Foster, S. et al.: Impact of irrigated agriculture on groundwater-recharge salinity: A major sustainability concern in semi-arid regions, Hydrogeology Journal, 26, 2781-2791, 2018.

Foster, S., and Garduno, H.: China: Towards Sustainable Groundwater Resource Use for Irrigated Agriculture on the North China Plain, GW MATE Case Profile Collection 8, World Bank, 16 pp., 2004.

Ganot, Y., Holtzman, R. Weisbrod, N. Russak, A., Katz, Y. and Kurtzman, D.: Geochemical processes during managed aquifer recharge with desalinated seawater, Water Resources Research, 54, 978-994, 2018.

Garduno, H. and Foster, S.: 2010. Sustainable Groundwater Irrigation: Approaches to Reconciling Demand with Resources, GW MATE Strategic Overview Series, 4, World Bank, 40 pp. 2010.

Gohari, A. et al.: Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin, Science of the Total Environment, 442, 405-419, 2013.

Herndon, R., and Markus, M.: Large-Scale Aquifer Replenishment and Seawater Intrusion Control Using Recycled Water in Sothern California, Boletin Geologico y Minero, 125, 143-155 2014.

IRIDeS: Fact-finding missions to Jakarta, Indonesia, International Research Institute of Disaster Science (IRIDeS), 86 pp. (available online: http://irides.tohoku.ac.jp/media/files/topics/irides_jakarta_2nd_report.pdf), 2013

Irvine, K., Chua, L., and Eikass, H.S.: The four national taps of Singapore: A holistic approach to water resources management from drainage to drinking water, Journal of Water Management Modeling, 1-11, 2014.

Kagabu, M., Shimada, J., Delinom, R., Nakamura, T., and Taniguchi, M.: Groundwater age rejuvenation caused by excessive urban pumping in Jakarta area, Indonesia, Hydrological Processes, 27, 2591-2604, 2013.

Lee, C.H.: The determination of safe yield of underground reservoirs of the closed-basin type, Transactions of the American Society of Civil Engineers, 78, 148-251, 1915.

Long, D. et al.: Global Analysis of spatiotemporal variability in merged total water storage changes using multiple GRACE products and global hydrological models, Remote Sensing of Environment, 192, 198-216, 2017.

MacDonald, A.M. et al.: Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations, Nature Geoscience 9, 762-766, 2016.

Madani K., AghaKouchak, A., and Mirchi, A.: Iran's socio-economic drought: Challenges of a water-bankrupt nation, Iranian Studies, 49, 997-1016, 2016.

430 Nabavi, E.: Failed policies, falling aquifers: Unpacking groundwater overabstraction in Iran, Water Alternatives, 11, 699-724, 2018.

OCWD (Orange County Water District): Groundwater Management Plan 2015 Update, (available at http://www.ocwd.com/media/3503/groundwatermanagementplan2015update_20150624.pdf), 2015.

Rahman, S.: Green Revolution in India: Environmental degradation and impact on livestock, Asian Journal of Water, 435 Environment and Pollution, 12, 75-80, 2015.

Rigaud, K.K. et al.: Groundswell: Preparing for Internal Climate Migration, World Bank, 222 pp., 2018.

Ritter, K.: Groundwater Plummets in Delhi, City of 29 Million, (available online: http://www.circleofblue.org/2019/india/groundwater-plummets-in-delhi-city-of-29-million/), 2019.

Rodell, M. et al.: Emerging trends in global freshwater availability, Nature 557, 651-659, 2018.

440 Rodell, M., Velicogna, I., and Famiglietti, J.S.: Satellite-based estimates of groundwater depletion in India, Nature, 460, 999-1002, 2009.

Schmanski, S.: Green Revolution Fallout Plagues India's Punjab Region, New Security Beat (available online http://www.newsecuritybeat,org/2008/08/green-revolution-fallout-plagues-indias-punjab-region/), 2008.

Sengupta, S.: New plan, old problem, (available online http://www.downtoearth.org.in/coverage/new-plan-old-problem-445 47387), 2015.

Seth, B.L.: Delhi groundwater, a deadly cocktail: CGWB report, (available online http://www.downtoearth.org.in/news/delhi-groundwater-a-deadly-cocktail-cgwb-report--40863), 2015.

Sharma, D.C.: Delhi's great water fall: Capital fears riots and water shortages as groundwater level hits dangerous low. Daily Mail, (available online http://www.dailymail.co.uk/indiahome/indianews/article-2288607/Delhis-great-water-fall-Capital-450 fears-riots-water-shortages-groundwater-level-hits-dangerous-low.html), 2013.

Siegel, D.: The future of American geoscience in the 21st Century: A speculation for reflection, Geological Society of America, Abstracts with Programs, 51, 1, Portland ME, 2019.

Singh, S. and Park, J.: Drivers of change in groundwater resources: A case study of the Indian Punjab, Food Security, 10, 965-979, 2018.

455 Smith, M., Cross, K., and M.L. Paden, M.L.: Spring – Managing groundwater sustainably, IUCN, 133 pp. (available online: https://portals.iucn.org/library/sites/library/files/documents/2016-039.pdf), 2016.

Sophocleous, M.: Managing water-resources systems: Why "safe yield" is not sustainable, Ground Water, 35, 561, 2005.

Wang, Y., Zheng, C., and Ma, R.: Review: Safe and sustainable groundwater supply in China, Hydrogeology Journal, 26, 1301-1324, 2018.

460 Watkins, M.D., and Bazerman, M.H.: Predictable Surprises: The Disasters You Should Have Seen Coming, Harvard Business School Press, 323 pp., 2004.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M.: Ground Water and Surface Water: A Single Resource, U.S. Geological Survey, Circular 1139, 79 pp. (available online http://pubs.usgs.gov/circ/1998/1139/report.pdf), 1998.

World Bank: Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India,
465 World Bank, 97 pp., 2010.

Ye, A., Duan, Q., Chu, W., Xu, J., and Mao, Y.: The impact of the South-North Water Transfer Project (CTP)'s central route on groundwater table in the Hai River basin, North China, Hydrological Processes, 28, 5755-5768, 2013.

Young, W.J. et al.: Pakistan: Getting More from Water, Water Security Diagnostics, World Bank, 163 pp. 2019.

Zheng, C. et al.: Can China cope with its water crisis? - Perspectives from the North China Plain, Ground Water 48, 350-354,
470 2010.

Wang, J. et al.: Groundwater irrigation and management in northern China: status, trends, and challenges, International Journal of Water Resources Development, International Journal of Water Resources Development, DOI: 10.1080/07900627.2019.1584094, 2019.

Wang, Y., Zheng, C., and Ma, R.: Review: Safe and sustainable groundwater supply in China, Hydrogeology Journal, 26,
475 1301-1324, 2018.

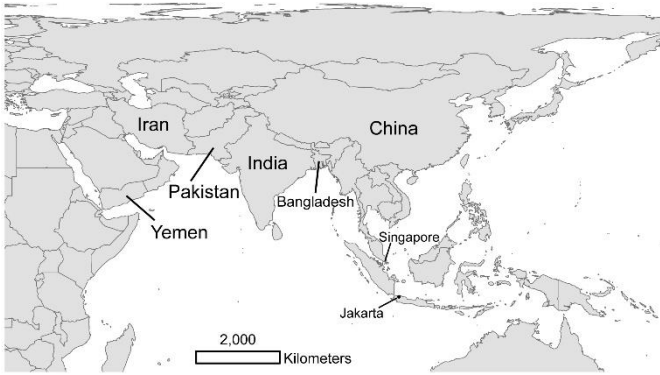
Watkins, M.D., and Bazerman, M.H.: Predictable Surprises: The Disasters You Should Have Seen Coming, Harvard Business School Press, 323 pp., 2004.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M.: Ground Water and Surface Water: A Single Resource, U.S. Geological Survey, Circular 1139, 79 pp. (available online http://pubs.usgs.gov/circ/1998/1139/report.pdf), 1998.

480 World Bank: Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India, World Bank, 97 pp., 2010.

Ye, A., Duan, Q., Chu, W., Xu, J., and Mao, Y.: The impact of the South-North Water Transfer Project (CTP)'s central route on groundwater table in the Hai River basin, North China, Hydrological Processes, 28, 5755-5768, 2013.

Young, W.J. et al.: Pakistan: Getting More from Water, Water Security Diagnostics, World Bank, 163 pp. 2019.

485 Zheng, C. et al.: Can China cope with its water crisis? - Perspectives from the North China Plain, Ground Water 48, 350-354, 2010.

490   **Figure 1: Map showing the Asian countries and cities discussed in the paper.**

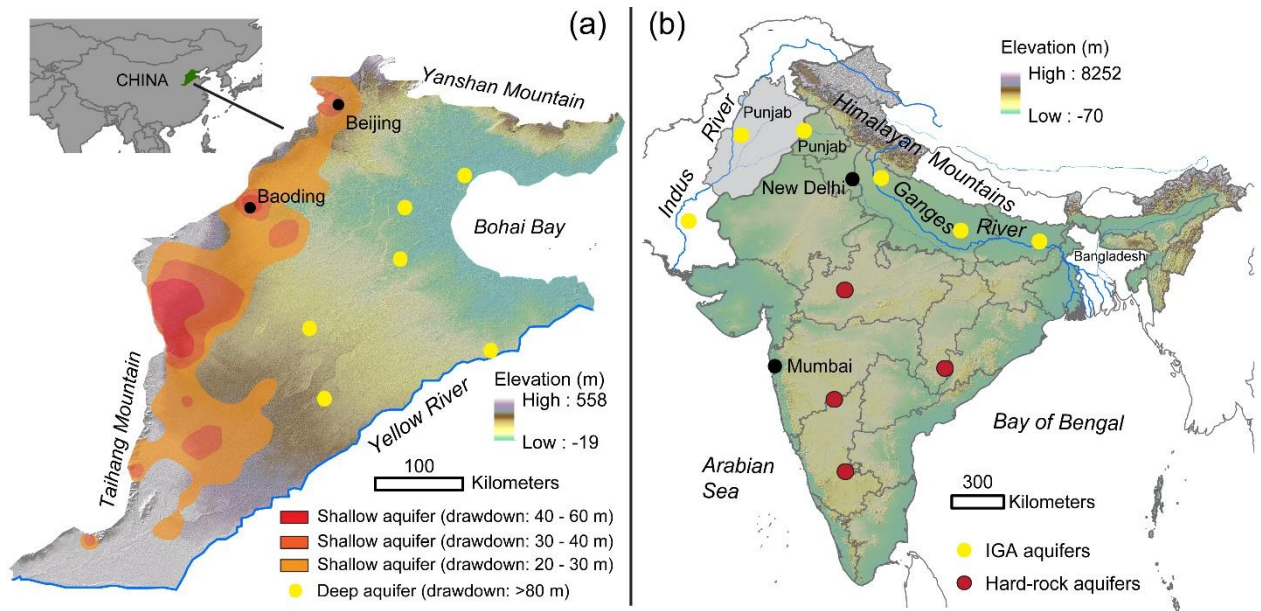



Figure 2: Panel (a) is a shaded relief map of the core of the North China Plain. The red/orange colored areas have drawdowns >20
495   **m in the shallow aquifer (Cao et al., 2012). The yellow dots indicate areas with local drawdowns in the deep aquifer >80 m (Zheng**
et al., 2012). Panel (b) shows India, Pakistan and Bangladesh. The red dots generally indicate the locations of hard-rock aquifers.
The yellow dots point to the general location of IGA system along the plains of the Indus and Ganges Rivers.

Text Box 1: Headlines and articles reacting to Delhi's worsening groundwater problems.

520

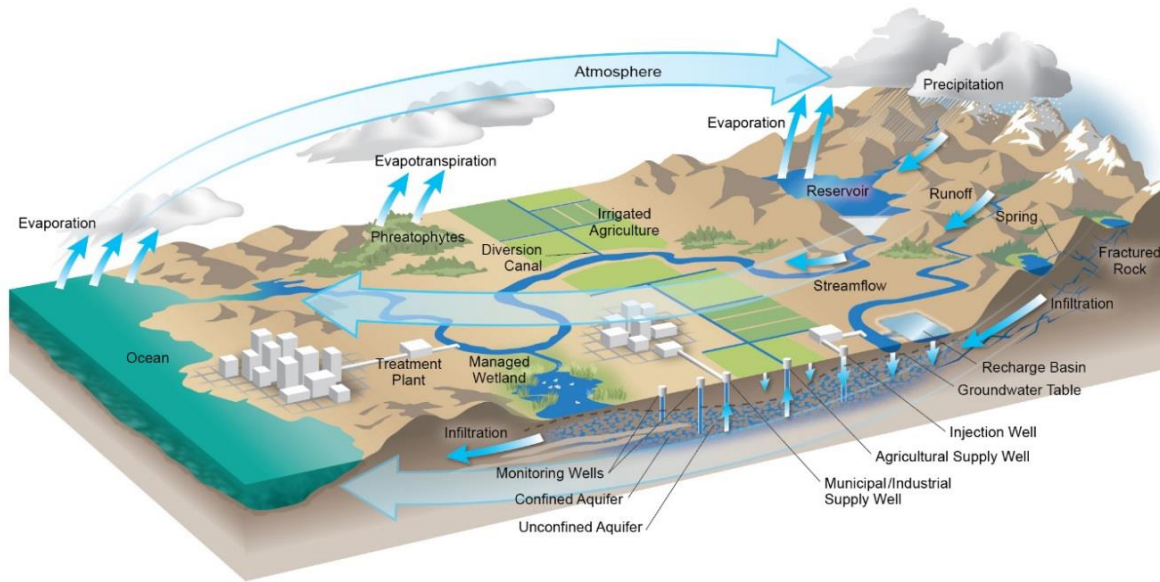
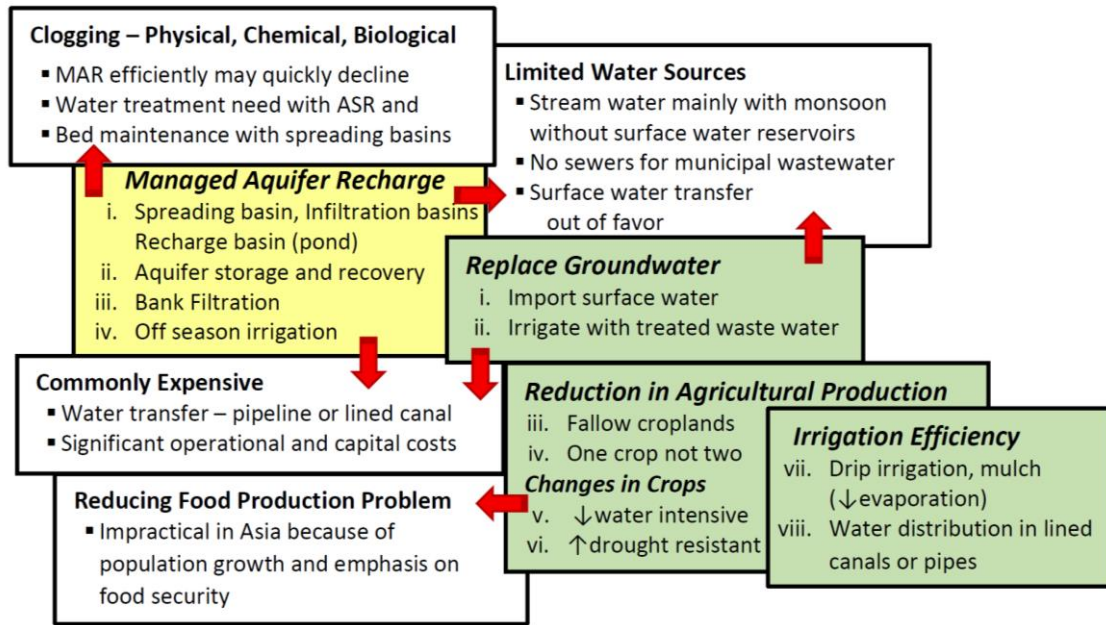



Figure 3: Conceptual model of a hypothetical coastal hydrologic system featuring a major river, cities, agricultural irrigation, an
525 **alluvial aquifer system being recharged using various MAR systems, and more. Complexities arise from (i) the number of different processes operating within the basin and their associated parameters, (ii) a need to quantify the diverse array of water exchanges within the hydrologic cycle, (iii) water uses that need to be metered, (iv) potential groundwater contamination from irrigation return flows, and (v) constraints dictated by sustainable groundwater management. (With permission, California Department of Water Resources, 2016).**

530

535 **Text Box: 2. The yellow and green boxes list some of the strategies for increasing aquifer storage of groundwater by increasing inflows through managed recharge and/or decreasing the quantity of water pumped, respectively. The red arrows indicate associated issues.**

540