https://doi.org/10.5194/hess-2019-399
Preprint. Discussion started: 12 August 2019

Hydrology and Earth System Sciences
Open Access
Discussions

HESS Opinions: The Myth of Groundwater Sustainability in Asia

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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 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 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 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, 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 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 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.

By rights, Asia should be far along towards groundwater sustainability. Earlier studies pointed out problems and posited 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 Few Signs of Progress and Worsening Trends

In China, India, Pakistan and other hotspots (Figure 1), groundwater continues to be impacted by groundwater depletion and contamination. 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 – $4.9\text{x}10^4\ km^2$in the 1990s → $7.9\text{x}10^4\ km^2$ in 2000s → $9\text{x}10^4\ km^2$ 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. Groundwater provides 85% of drinking water and 60% of water for irrigation (World Bank, 2010). There two prototypical settings for groundwater. 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 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 regionalized. 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 geogenic arsenic in groundwater associated with sediments from Himalayan sources (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 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 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).

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 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 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

https://doi.org/10.5194/hess-2019-399
Preprint. Discussion started: 12 August 2019

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 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 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?

Developing Asian countries have encountered significant roadblocks hindering progress towards groundwater sustainability. So far, it has been relatively painless for countries and large cities to simply 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.

An instructive example is Yemen, a slowly unfolding example of human tragedy. Yemen is located at the southern end of the Arabian Peninsula bordering the Red Sea. After four years of civil war, half the population (~28 million) is short of water (Camacho et al., 2018). Approximately 60% of the population is food insecure with nearly 500,000 children under five suffering "severe acute malnutrition" (BBC, 2017). The public health system has trouble providing basic services in the face of the world's largest recorded epidemic of cholera in modern times. There have been more than one million cases from 2016-2018 (Comacho et al., 2018). It is easy to understand why problems of groundwater over-pumping evident even in 2002 in the Sana'a basin (Foster, 2003) are not an urgent national concern.

In Asian countries, much less deference is given 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 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, 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 to reduce the production of food and groundwater.

The second major impediment to progress in sustainable management is the inherent inability to manage anything that is not understood. For example, assuming that appropriate laws and regulations exist, government administrative actions, such as authorizing or charging for groundwater use, banning new wells, or capping production with existing wells (Garduno and Foster, 2010), all depend on data. The solution to groundwater requires an understanding of the scope and extent of problems and specific information as to who is pumping what quantities of water. Populous developing countries quite simply may lack the capacity to administer groundwater.

Modern technical or socioeconomic interventions in support of aquifer sustainability depend on data for planning purposes and compliance monitoring to assure actual progress towards sustainability goals. This kind of data-centric approach is different than, for example, traditional water-harvesting methods understood to promote groundwater recharge and storage. For example, India is the world leader in the number of these traditional systems installed (Dillon et al., 2019). There are "several million recharge structures" (Dillon et al., 2019) in place, some quite old, and 11 million more planned. Typically, this type of managed aquifer recharge (MAR) has involved streambed recharge and percolation tanks/ponds to store water in the subsurface. Yet, there are few quantitative assessments of the efficacy of these approaches in promoting recharge (Dillon et al., 2019; Dashora et al., 2018). While contributing to sustainability, these practices are unlikely to achieve that goal. Moving beyond India to China and S.E. Asia, there are few active MAR projects in operation (Dillon et al., 2019).

A program invested in groundwater sustainability requires personnel with basic knowledge of hydrogeology along with specializations in relevant topical areas. Such specialized knowledge exists in the world, but not so much in Asian countries. Until this expertise is developed and embellished through practical experience, progress will continue with the *ad hoc* traditional practices.

This idea of "understanding" in relation to the sustainable management of groundwater must extend to comprehensive national data collection, such 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 some progress in China but information there is siloed and lacking in necessary transparency. In the megacities, like Jakarta, Delhi, and Karachi, our reviews found the status of groundwater data to be meagre to nonexistent, totally inadequate to support technical or socioeconomic efforts towards sustainability.

The kinds of technical information and infrastructure needs 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, 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 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 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 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 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 are commonly not persuaded that 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)

There are successful models for managing water resources sustainably. They are worth discussing here to illustrate (i) requirements for data and advanced technologies, (ii) the long-term commitment to complex and costly projects, and (iii) efforts necessary to turn urban wastewater into a valuable water source. The Orange County Water District (OCWD) in southern California near Los Angeles is a leader in sustainable groundwater management. OCWD serves a 900 km^2 area, distributing water to ~2.4 million people. Two thirds of that water comes from groundwater produced from hundreds of deep, high capacity wells. Sustainable operation of the aquifer systems provides ~345 Mm^3 yr^{-1} of high-quality groundwater, while maintaining aquifer storage within a specified operating range (Hendron and Markus, 2014). With natural recharge of only 74 Mm^3 yr^{-1}, sustainable management requires additions to storage through MAR (Hendron and Markus, 2014). Water is diverted from the Santa Ana River and infiltrated through recharge basins (Figure 4). River flow is mostly treated sewage and occasional winter stormflows.

Another recharge source is purified water produced by the Groundwater Replenishment System (GWRS) facility (Figure 4). Municipal wastewater, collected and treated at the Orange County Sanitation District (OCSD) treatment facility, is transferred to the GWRS facility for advanced treatment (Hendron and Markus, 2014). Processing that includes reverse osmosis and other treatments produces near-distilled water. Approximately 65% of this water moves through pipes to recharge basins at Anaheim (follow the red line, Figure 4). The remainder is injected through a line of wells completed at various depths, creating a seawater intrusion barrier.

A simple water-balance (Eqn. 1), based on Hendron and Markus (2014), shows pumped groundwater (PGW) to be balanced by natural recharge (NR), MAR using both infiltrated river water (IR) and advanced treated wastewater (ATW):

$$74 \text{ Mm}^3 \text{ yr}^{-1}{}_{\text{NR}} + 185 \text{ Mm}^3 \text{ yr}^{-1}{}_{\text{IR}} + 86 \text{ Mm}^3 \text{ yr}^{-1}{}_{\text{ATW}} - 345 \text{ Mm}^3 \text{ yr}^{-1}{}_{\text{PGW}} = 0 \quad (1)$$

The success of OCWD's hydrogeological operations is critically dependent on monitoring. They collect production data monthly for the high capacity production wells and less frequently for smaller wells (OCWD, 2015). Water level and water quality data coming from hundreds of wells provides evidenced-based compliance with sustainability goals. The quality of water from the GWRS facility is monitored, as is the Santa Ana River and tributaries (OCWD, 2015). Performance of the seawater intrusion barrier is also monitored along with subsidence across the basin.

Such sophisticated water management systems are uncommon in Asia. Yet, 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).

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. 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. Groundwater-related problems are largely invisible (Biswas et al., 2017) and seemingly irrelevant to a greater agenda. For China, India, 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.

Despite progress with satellite-remote sensing, particularly GRACE (Feng et al., 2018; Long et al., 2017; Rodell et al., 2009; Rodell et al., 2018), actions around evidence-based groundwater sustainability is at an early stage. In the case of the IGA aquifer system, the greatest present threat to long-term sustainability is not from over-pumping but from human activities that have led to groundwater salinization and urban/agricultural contamination (MacDonald et al., 2016). This experience in India and Pakistan and possibly China reveals how pervasive contamination can lead to the same unsustainable outcome as over-pumping.

Adding water-quality issues to the sustainability mix reveals even greater deficiencies in data and needs for research in modeling and arid-zone geochemistry. For example, 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 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. Research is required to explore mechanisms, pathways and time scales of contaminant-related impacts on sustainability of aquifers. Another target of opportunity is the difficult field characterizations of the geochemistry of saline groundwaters in arid-zone settings.

A pragmatic research agenda must also account for the risk that sustainable groundwater management will never happen. The necessary transition from a water policy of muddling along, stumbling from one crisis to the next without substantive actions to quantifiably sustainable systems, like those in Orange County or Singapore will be enormous. Further, it is doubtful whether the successful strategies in those two places with relatively small and economically advantaged populations are practically scalable to many millions of people in developing countries. In any case, logistical constraints mean that it will be decades before 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).

It is worthwhile to consider research to support those sustainability initiatives that are likely to be undertaken. For example, India appears poised to invest in traditional MAR schemes (Dillon et al, 2018). There are significant opportunities in reimagining this overall approach by adapting modern practices to the design and restoration of traditional water-harvesting systems.

Another possibility is for research to facilitate adaption to the worst outcomes. This idea came from a recent conference address (Siegel, 2019), which challenged the audience to contemplate a future where researchers are consumed in dealing with problems of adapting to unmitigated impacts of climate change. A population-modeling study gaging the future in-country migration in arid countries due to climate change (Rigaud et al., 2018) is an interesting example. The results for South Asia suggested that by 2050, there could be 35.7 million in-country climate migrants under a pessimistic climate scenario.

In the context of groundwater sustainability, we envision a need for research that would help with adapting to the ongoing decline in groundwater availability aggravated by climate change impacts. In other words, with groundwater sustainability unlikely to be achievable, research could help in understanding when the groundwater is likely to run out, possibilities for creatively stretching the supply, or envisioning ways to ease the impacts of inevitable declines in food and health.

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/
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 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.

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.

BBC, Yemen conflict: How bad is the humanitarian crisis?, (available online: http://www.bbc.com/news/world-middle-east-34011187), 2017.

https://doi.org/10.5194/hess-2019-399
Preprint. Discussion started: 12 August 2019

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 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), 2017.

Camacho, A. et al.: Cholera epidemic in Yemen, 2016-2018: An analysis of surveillance data, The Lancet, 6, e680-e690, 2018.

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.

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.

Foster, S.: Yemen: Rationalizing Groundwater Resource Utilization in the Sana'a Basin of Yemen, GW MATE Case Profile Collection 3, World Bank, 12 pp. 2003.

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.

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.

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, 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.

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-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-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.

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.

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, 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, 2010.

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

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

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Preprint. Discussion started: 12 August 2019

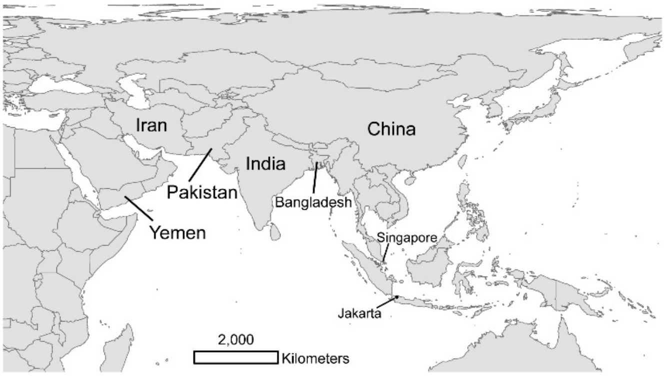

Figure 1: Map showing the Asian countries and cities discussed in the paper.

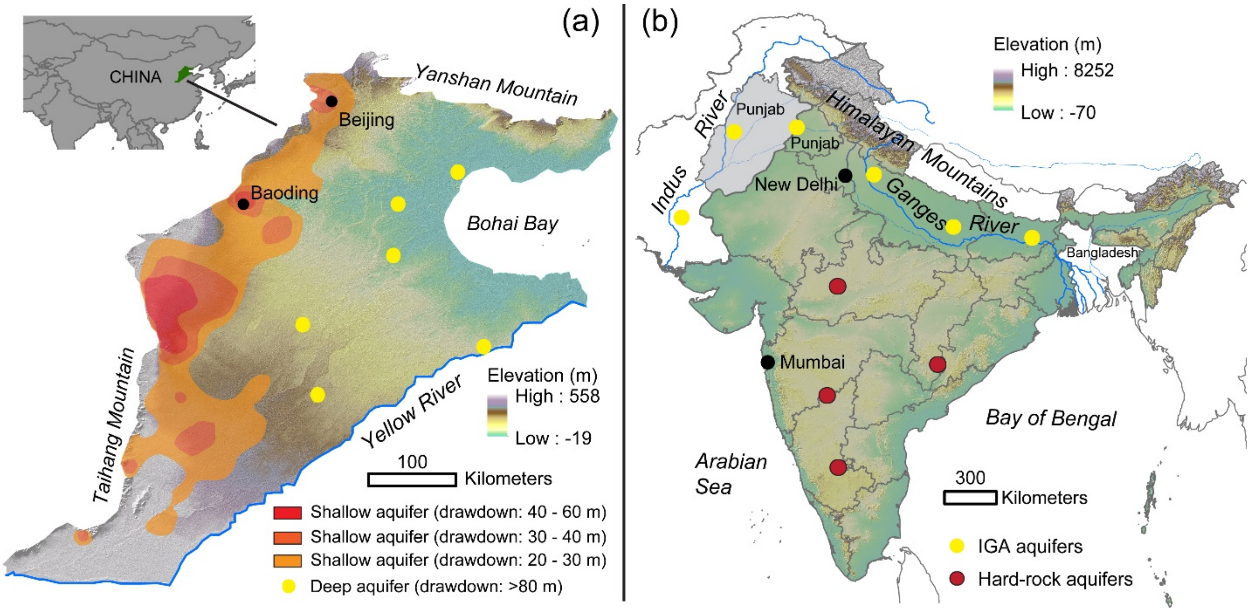

Figure 2: Panel (a) is a shaded relief map of the core of the North China Plain. The red/orange colored areas have drawdowns >20 m in the shallow aquifer (Cao et al., 2012). The yellow dots indicate areas with local drawdowns in the deep aquifer >80 m (Zheng et al., 2012). Panel (b) shows India, Pakistan 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.

Delhi's great water fall: Capital fears riots and water shortages as groundwater level hits dangerous low

- S and SW Delhi water table declined 10-20 m last 10 yrs
- At 20-50 m water brackish or saline
- Contamination by NO_3, F (Sharma, 2013)

Delhi groundwater, a deadly cocktail

- 42 of 124 samples salinity 2000 to 16,700 uS/cm
- 6 of 122 NO_3 800-1500 mg/L
- 29 of 122 NO_3 100 -800 mg/L (Seth, 2015)

Groundwater Plummets in Delhi, City of 29 Million

- Could reach "zero groundwater levels" by 2020
- 390 M m^3/yr groundwater pumped vs. natural recharge 310 M m^3/yr
- groundwater levels critical in 90% of city and demand is growing (Ritter, 2019)

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

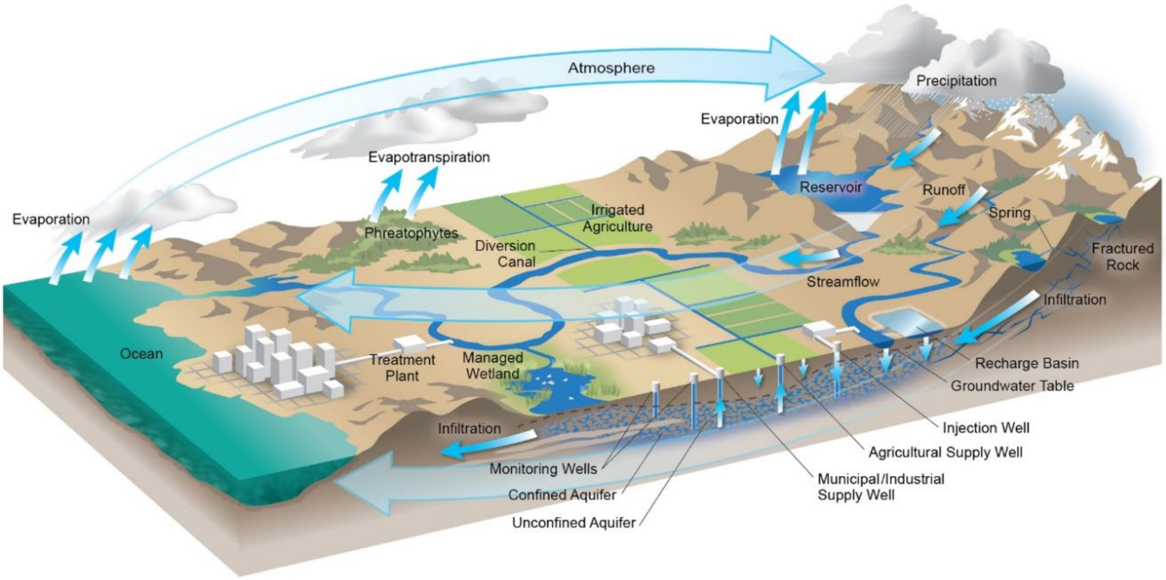

Figure 3: Conceptual model of a hypothetical coastal hydrologic system featuring a major river, cities, agricultural irrigation, an alluvial aquifer system being recharged using various MAR systems, and more. Complexities arise from (i) the number of different processes operating within the basin and 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).

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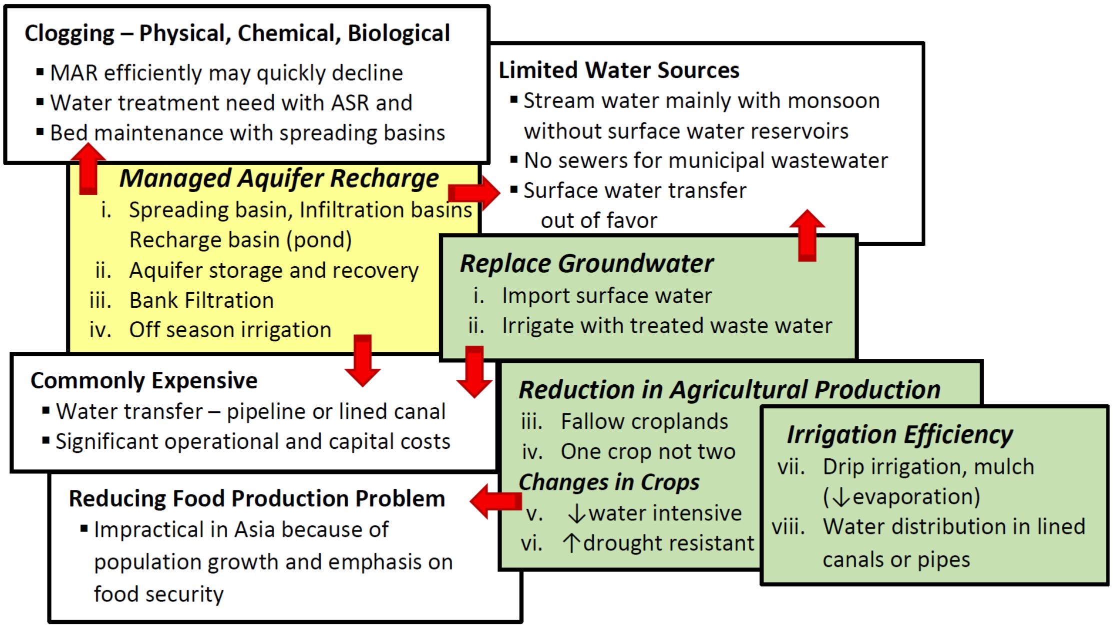

Text Box: 2. The yellow and green boxes list some of the strategies for increasing aquifer storage of groundwater by increasing inflows through managed recharge and/or decreasing the quantity of water pumped, respectively. The red arrows indicate associated issues.

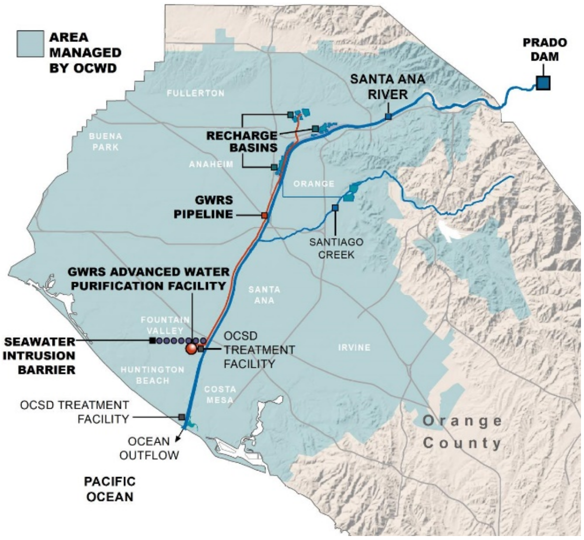

Figure 4: Facilities operated by the OCWD (With permission, Orange County Water District, 2015).