We are appreciative of the constructive comments on the paper from all three reviewers. We have considered them carefully and made significant changes to the paper. Most every comment, led to a change in the manuscript that addressed the reviewer's comments. The following pages discuss the specific changes made for each of the reviewers.

Responses to Reviewer #1:

The opinion paper by Frank Schwartz and coauthors discusses the lingering groundwater crisis in several Asian countries, some reasons how it could come so far, theoretically feasible technical solutions, and vague research directives. It is clear, that groundwater exploitation is not sustainable in many countries with (semi)-arid climate, including actually large parts of the United States.

1. However, besides climate and land use there are also societal boundary conditions, and these differ tremendously between the countries discussed in the manuscript.

The original paper draft was focused on mainly technical issues that we considered as hurdles that needed to be overcome for quantitative and verifiable management of large aquifers. Our view was that these issues for many countries in Asia constituted barriers that by themselves would preclude serious efforts towards sustainability. In this respect, the availability of data represents a critical information gap for many countries because you cannot manage something you don't understand. We also used experience from Orange County, California and California more generally to illustrate the true challenges of sustainable management of groundwater from a technical perspective.

However, Reviewer #1 quite rightly pointed out that sustainable management also requires a proper legal and socio-economic framework for action. Our paper hinted at the necessity for laws as basis for enforcing limits on withdrawals and synchronization of macroeconomic policies, but the coverage was minimal. Following the reviewer's suggestion have ***we expanded the paper significantly*** *to explain frameworks for action and the various components that contribute to sustainability, and to provide a context for key countries that we considered.*

We address points 1 and 3 together by adding a long section [lines 35 to 63] in the introduction that describes robust frameworks shown to work in areas of legislation, policy, regulatory/macroeconomic tools. In section "3. What are the Hurdles to Groundwater Sustainability?" we have rewritten and generalized the 2nd "hurdle" concerning data to describe the status of India, Pakistan, and China [lines 189 to 218] with respect to the socio-economic framework discussed in the introduction. The treatment is economical (adding ½ page new) and a significant rewrite of associated material.

2. The People's Republic of China definitely does lack democratic participation, but it has a long standing tradition of a functional administration, and the economic growth of the last decades has led to the economic foundation for expensive technical solutions, if applicable. We see this in water treatment (both for freshwater and waste water) where tremendous progress has been made in recent years. Of all countries discussed in the manuscript, China is the one where the educational and administrative conditions are the best to implement water-management strategies comparable to those of Southern California - if the Communist Party decides sustainable groundwater management to be an important issue. In contrast, other countries lack the concept of groundwater rights.

We have added a section explaining the present status of groundwater management in China as well as Pakistan and India. The China piece is part of the longer section described in 1 above (3rd paragraph) *lines [189-218] in the manuscript. Assessments by various authors indicate much slower progress in groundwater management than with surface water. We added the sentiment that China would have the financial and technical capacities if the government wished to make progress.*

"However, China does have the fiscal and technical capacity to support projects focused on sustainability."

3. If traditionally the owner of a piece of property is allowed to extract all resources thereof, including groundwater, implementing rules of sustainable groundwater management is doomed to fail. There must be an accepted legal framework stating that you don't own the water of the land that you own, that drilling and operating a new well requires a permit, that the permit can only be issued based on a management plan of the entire resource, that abiding by the rules must be monitored, and that a breach of regulations must be punished. If this basic societal understanding does not exist, sustainability cannot be enforced.

As mentioned, this is a specific example of the socio-economic issues discussed in 1 and has been addressed in the revision.

4. I don't think that the authors should put Yemen into the mix of countries to consider. Yemen has been in a Civil War for years, and one cannot expect that anything functions. Almost the same would hold for Afghanistan where the German Geological Survey had spent millions on developing groundwater management rules, including hydrogeological mapping and implementing groundwater monitoring. All of that disappeared when the security of western advisors was no more guaranteed. In such dysfunctional countries, sustainable groundwater management cannot be of high priority. Whereas it could in India.

Rev#1 and Rev#2 both recommended that we remove this piece. ***We have done so****.*

5. The authors present Orange County and Singapore as highly developed regions in which technical solutions for sustainable groundwater management have more or less successfully been implemented, monitored, and maintained. They could add Israel where advanced irrigation techniques and managed aquifer recharge has been developed on a world leading level. Like in Singapore, if even not much more so, Israel is in need of self-sufficiency, has a functional administration, and is home of some of the best engineers worldwide. Hence, when it comes to discussing why sustainable groundwater management appears achievable in Israel but not so much in some of its neighboring countries with similar climate and geology, the societal and governmental boundary conditions must be analyzed to a depth at which geologists and engineers feel uncomfortable. Being a hard-core scientist myself, I lack an in-depth discussion of societal differences among the different countries that can explain differences and give predictions on the chances of implementing sustainable groundwater management practices. Iran, India, China, and Pakistan are quite different countries.

Israel is certainly worth noting as a country with success in managed aquifer recharge. We have added sentences to the discussion at this point in the paper discussing accomplishments in Israel. In our revision, we have pointed out our view as to why Orange County, Singapore, and Israel have been successful (from paper).

"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 modern and reliable infrastructures, and (iii) a manageable problem scope stemming from relatively small populations.."

We agree with the reviewers comments in the last few sentences of 5. As mentioned in 1 and 3 we have provided a much improved analysis of the legislative and operational "boundary conditions" to provide a better sense as to which countries are likely to succeed.

6. The authors rightfully point to water-quality issues related to groundwater management in arid climates and/or regions of intensive agriculture. However, you don't need to go to Asia to realize that salt accumulation in over-exploited aquifers is an issue largely unrecognized by many groundwater managers. In large parts of the western United States, a continuous increase in salinity has been observed in conjunction with declining groundwater levels. At the end of the day, balancing the volume of water is insufficient to obtain sustainability in systems undergoing strong evapotranspiration. We may come to the conclusion that managing the dissolved solids will require more aggressive treatments, such as membrane-based deionization before artificial groundwater enrichment. Luckily, the electricity needed for that can be gained by photovoltaic power in the arid regions that require such treatments the most. Likewise, arsenic (or fluorine) can be removed by technical treatment, but the premise of centralized water treatment is a centralized water supply. In as much, technical solutions for the supply of cities, where centralized treatment options are achievable, must differ from technical solutions for drinking water supply and irrigation agriculture in rural regions. And neither will work without a functional and responsible administration.

The paper already makes clear there is more to sustainability than taking care of water balances. Indeed this is evident as we mention in both India and Pakistan. We think the points raised here concern remediation membrane-based deionization, arsenic removal, are interesting but are much further in the future. Largely, the character, distribution and concentration remains an informational black hole for all these countries including China. So, we made no changes in this respect but as the reviewer will note (see Reviewer #3 responses) we have addressed technologies as a driver to sustainability.

7. With respect to research directives, I highly recommend prioritization. Western researchers are interested in exciting science, but that is not always the gateway to practical solutions. Understanding the release and fate of arsenic in deltaic aquifers in south-east Asia is an example of a scientifically challenging question. Alas, among the hundreds to thousands of publications on mechanistic questions related to arsenic in south-east Asia, only a few have been useful to help the people affected. There have been examples in which "cool" science actually contributed to developing sustainable groundwater

management strategies, but most of the science is done by the flock of academic sheep following a research bellwether. Most likely, raising the level of education in water-related sciences is the best that university scientists can do to contribute; we need to train people with a solid understanding of hydrogeology and environmental engineering, who hopefully reach positions where they can make decisions. But how a society has to change that responsible decision making by administrative authorities is implemented and accepted, I have no clue.

We heartily agree with these comments. Obviously, the scope and scale of existing and future problems are too serious to be poking around answering basic-science questions. We have both reworded and added sentences in the conclusion to reflect this view from Rev#1 as follows.

"There are basic technical approaches that have the potential contribute to sustainability. For example, several countries are already invested in recharge projects, India with their tradition MAR (Davis et al., 2018) and China with their "sponge city" concepts. Significant opportunities exist in identifying strengths and weaknesses with these methods, and in optimizing the benefits for groundwater sustainability. To be most useful, studies should focus on best practices appropriate to the economic and technical capacities of the countries involved."

A few minor comments.

1. line 33: Replace "by right" with "basically". Non-native speakers think you refer to a legal term.

DONE

2. lines 43-44: Are there only one continuous shallow and one continuous deep aquifer in the entire North China Plain? Otherwise use the plural. OK as is

3. line 58: Do the percentages refer to India or are the worldwide numbers? The same question refers to the "two prototypical settings for groundwater". Word "India" added twice in clarification

4. line 63: "recover to the levels of previous years" or "recover from the withdrawals of previous years." Latter is correct.

5. line 77: The term "regionalized" appears odd here. This is a term used in geostatistics for interpolation of point data, but it seems you mean "restricted to certain regions". DONE

6. line 81: While the root cause of arsenic in the IGA system is in the Himalayan sediments, the mechanism are more complicated. I suggest dropping this explanation in order to avoid oversimplification. DONE

7. line 92: Nitrate is sometimes measured as concentration nitrate, and sometimes as concentration nitrate-N. Be specific! No change because not clear in the original report. We followed their usage rather than guess.

Responses to Reviewer #2

1. This is an interesting opinion paper on a well-known and significant topic. I enjoyed reading it, especially the review on the case studies and the main problems hampering the effective and sustainable management of groundwater resources. To my best knowledge, the "myth" of groundwater sustainability, and groundwater management in general, belong to many countries, even "advanced" ones, not only Asian.

We appreciate Rev#1's kind comments here. We added the following point that groundwater sustainability belongs to many countries to the Introduction. (from paper) *"For many of these countries and even others outside of Asia, groundwater sustainability is essentially just a myth."*

2. The paper is made of two parts: illustration of selected examples and some proposals for a "pragmatic research agenda". The first part is quite good and convincing, although the main conclusions are unfortunately rather obvious and well known nowadays. The collection of cases is not a comprehensive review of groundwater management casein Asia, and it is not meant to be that, but it delivers the message; still, the socio-political conditions are much different among sites such that a comparison is not possible. Perhaps the main focus of the hurdles is on the technical issues, less on the sociopolitical constraints that in many cases lead the process.

We agree with Rev#2 that the focus of the original draft was on technical issues. Yet, as Reviewer #2 indicates, "the socio-political constraints" do indeed lead the process. Given that Rev #1 raised this same issue, we recognize that our "hints" about the importance of this aspect were insufficient. We addressed this weakness of the paper by adding ~1 page in the introduction, discussing the socio-economic frameworks, policies. We rewrote Section 3 and added material describing the policy constraints with respect to Pakistan, India and China so it is possible now to compare the status of these countries much more rigorously. The new material (beyond editing what was there) added about ½ page of additional things. You can find this material on lines 189-218.

3. My main reservation is that the exposition looks confusing at times. For instance, the examples continue in Section 3 (by the way, the case of Yemen seems to me quite divorced from the rest standing the particular situation of the area) and one cannot truly see a discontinuity between sections 2 and 3.

We made revisions along the lines suggested by the reviewer to reduce the confusion. The piece on Yemen is removed as both reviewers suggested.

We have retitled Section 2 "2 Trends in Depletion and Contamination of Groundwater Continue to Worsen" and modified the introductory sentence to "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." to better differentiate Sections 2 and Section 3.

4. The lengthy text on the OCWD seems quite out of place and not in line with the rest, which focuses on Asian countries (and do we need Eq.1?). A few sentences would have delivered the same concept. Similar for the Singapore case.

Our rationale with the longer section on OCWD was first to make sure that readers really understood that there are places where quantitatively verifiable groundwater management was taking place. Second we wanted to give a sense of the effort and money needed. This being said, we have trimmed this *section substantially and removed the figure. Previously, it was 388 words with a figure. Now it is 193 words, no figure and equation 1 removed.*

5. The second part, i.e. the delineation of the proposed ideas based on the current management practice in Asia, is much shorter than the first one and not much clear in my view. It definitely needs more elaboration. The Section promises “Groundwater Research Directions” but I can’t really find clear and sufficiently elaborated indications. The first item deals with water quality; adding water quality to the management practices seems rather obvious, and it is simplicitly done in several cases, but perhaps I have misunderstood the point (and the short text does not help).

In response to comments from Reviewer #1, we have added two very substantial sections – one to the introduction (1 pg) and the second to section 3 (~2/3 pg). The piece in the introduction explains what basic features of a groundwater management scheme should include, and particular socio-economic tools known to incentivize less pumping. In section 3, we have explained how well (or poorly in this case) aligned China, India and Pakistan are with to this framework. This we think is a reasonable response to “more elaboration” comment.

Concerning the promise of “groundwater research directions”, the best idea we had was research assuming that a lack of sustainability would create water shortages research could be useful in that area. The present draft has abandoned this idea as reviewers considered this too negative, and so laying out a research agenda is much less of a priority. So we have dropped the promise of research ideas and instead offered a few technology suggestions wireless monitoring and new GRACE and work on traditional approaches. We also recast research in water quality as a first simple step for management as suggested.

6. I agree in principle with the approach of considering the sustainable groundwater management as something that will never materialize, and the derived idea of the worst case scenario. This is something interesting and useful, and sometimes I have seen a similar approach adopted in practical management schemes. However, I see two problems with this approach. First, the analysis of the worst case scenario may anyway need significant resources for data acquisition and the understanding of the groundwater-surface water interactions, and then the several technical problems illustrated in the paper come back again.

Second, the message that may easily come out from this suggestion is the following: forget about management, too difficult and expensive, just let things go and prepare for the worst. That would mean the death of the concept of sustainable management and the triumph of “Business As Usual, with likely disastrous consequences on areas characterized by poor or absent management.

Reviewer #2, similar to Dr. Fogg Reviewer #3, is concerned about the negativity in the conclusion that suggested nothing is going to happen with sustainability and researchers need to get on with adapting to that reality. As mentioned in the comments to Reviewer #3, we have largely rewritten the conclusion. Gone is the negative view that implies business as usual by getting rid the concept of research planning for the worst. We have changed the heading to section 4 and added more information explaining a new and potentially important role for technology. We think these changes have responded to points 1 and 2.

7. Instead, I think that a less pessimistic alternative would be to provide a management procedure made by subsequent steps of increasing complexity, starting from basic and simple analyses that may guide

the management and political decision; in other words, not give up the concept of management. In this perspective, one would rather speak of “feasible management”, i.e. based on analyses that can be realistically carried out under the several constraints, starting from the simple concept of safe yield that is relatively easy to estimate in most cases. The governments and stakeholders may start making decision (import food? Invest more on different sources of water? etc.) from those basic and anyway fundamental pieces of information. Role of the scientists and engineers is to try to provide simple rules to stakeholders and managers, while complex management techniques may be affordable only by California or a few other developed regions. To this matter, the list of technical requirements brought by the paper is certainly discouraging. Thus, while the worst case scenario is something worth performing (but how about its uncertainty? Are the future stressors certain?), giving up completely the idea of management might not be so good. Again, I might have misunderstood the concept, and this part of the paper (Section 4) needs further clarification and elaboration.

As mentioned in response to point 5, we think in retrospect that promising research directions was an over-reach. So this concept is gone from the previous section title and the paper has been made less pessimistic by discussing new possibilities for future monitoring and management that might come from wireless networks and GRACE. We have encouraged “feasible management” by recasting the MAR approaches (both in India and China) are currently using in a much more positive light.

“There are basic technical approaches that have the potential contribute to sustainability. For example, several countries are already invested in recharge projects, India with their tradition MAR (Davis et al., 2018) and China with their “sponge city” concepts. While, these approaches are represent an important first step to groundwater sustainably, they are no panacea. For example, tradition approaches to water harvesting in India are not well suited for hard-rock areas, impact downstream users, and often lead to more pumping (World Bank, 2010).”

We did not add specific suggestions about simpler management strategies for two reasons. First, The World Bank has done a great job in promoting practical, country-specific strategies – we added a sentence to the conclusion saying this. As changes prompted by Reviewer #1 has shown, the bottleneck of capacity and fractured policy is so severe that it is difficult to accomplish even simple changes. Second, this is outside the scope of the paper, and adding a small piece to the conclusion would not contribute much.

Responses to Reviewer#3 – Dr. Fogg

This Opinion paper is a well-written, sobering description of the ongoing crisis of groundwater mismanagement in Asia and prospects for changing course. Despite its negative bottom-line message that the crisis likely cannot be averted, I enjoyed reading the paper and believe the readership will find it interesting and thought provoking.

We appreciate Dr. Fogg's comments here.

All of my edits and comments are marked directly in the PDF that is uploaded with this review.

We examined Dr. Fogg's pdf that provided comments on specific phrasing, and more substantive ideas. We made appropriate modifications to the manuscript that reflected his suggestion in all instances.

My main comment is that the message - that it's highly unlikely for groundwater in Asia to ever be managed sustainably- is too negative. Granted, this is an opinion piece, and the authors are entitled to their opinion, but I think they might be missing an opportunity to provide more impetus for positive change. I worry that the negative message may do more to stifle groundwater management than to produce beneficial change, and all under the assumption that such change is impossible.

Dr. Fogg's comment on the message being too negative is similar to comments that came from Reviewer #2. We accepted both their points of view and responding by rewriting the conclusion to brighten it up. Most importantly we have deleted the idea of "planning for the worst". In other words, we leave the far future to the readers' imaginations without explicitly stating that sustainability won't happen. This has led to changes in the title to section 4 and the concluding paragraph and paragraphs describing research on adaptation. As we mention with specific following comments, we have added several sentences in the conclusion that specifically reflect Dr. Fogg's perspective (below).

Dr. Fogg made a comment before the conclusion that made the point that traditional MAR was a very good thing, rather than some incremental effort that we implied. The revision of the conclusion also put a much more positive "spin" on the efforts in India and China.

"There are basic technical approaches that have the potential contribute to sustainability. For example, several countries are already invested in recharge projects, India with their tradition MAR (Davis et al., 2018) and China with their "sponge city" concepts."

For added perspective, consider the following:

- Any of the needed groundwater information infrastructure would be cheap relative to the spending these countries are currently doing for construction and maintenance of surface water infrastructure (dams and conveyance). So if they realize they must have something, they can likely find the means to achieve it. One less dam project could free up enough funds for a national groundwater monitoring network. Thailand's Department of Groundwater (yes, there is such a thing) has been doing this nationally since the 1950-60s and hence has been more proactively managing groundwater.

We have no disagreement with what Dr. Fogg has written here. The manuscript was confusing about what kind of infrastructure we were considering to be expensive. The infrastructure we wrote about was that required to provide for new sources of water for MAR. For example, imported water, might require dams and canals. Using domestic wastewater in India as a source, would require adding, expanding and *upgrading sanitary sewer systems, re-imagining the waste-water treatment facilities, MAR and making electric power more reliable. We have added clarification to the text on this point.*

- The world may be entering a period of change with respect to groundwater man-agement, although it may require considerable coaxing and crises to get there. Since widespread deployment of industrial scale groundwater pumping technologies some 70 yrs ago, very little effort has been devoted to recharging and managing ground-water. In essence, civilization has not yet begun to try to manage groundwater very much, mainly because it has not had to, mainly because of the vastness of most groundwater basin resources. But now that may be starting to change. See the discussion piece: https://trend.pewtrusts.org/en/archive/spring-2019/groundwater-the-resource-we-cant-see-but-increasingly-rely-upon. I agree - it is questionable whether such change can happen soon enough in Asia, and people should also start preparing for the worst.

The conclusion was modified to reflect this viewpoint through the addition of a sentence and reference to Dr. Fogg's paper.

(from paper) "It may also be that groundwater is so plentiful that it has never been a concern (Fogg, 2019)."

- One could argue that a big part of the problem is the lack of transparency of groundwater systems, making the state of gw resources easier to ignore. There are technologies coming along that could change this significantly - e.g., low-cost wireless, real-time groundwater level monitoring networks connected to open-source web platforms to track fluctuations in groundwater levels (these may require cellular networks, which are already more extensive in parts of rural Asian than parts of rural America); and future

We also added words to suggest that monitoring could be a catalyst to increase visibility.

"There is, however, some hope that new technologies may create sufficient visibility as to the severity of the groundwater problems to finally spur action (Fogg, 2019)."

We also made particular reference to real-time monitoring and GRACE follow-on mission as being examples of helpful new technologies.

"There is, however, some hope that new technologies, may create sufficient visibility on the severity of the groundwater problems to finally spur action (Fogg, 2019). For example, there are relatively inexpensive, wireless technologies available for monitoring water levels in real time. Expected improvements in satellite-remote sensing, particularly future GRACE missions, are also expected to enhance our understanding of aquifers worldwide (Fogg, 2019). "

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. Fragmented governance and the general inability to bring traditional socio-economic tools to bear on reducing groundwater demands have impeded progress to groundwater sustainability. For India and Pakistan, where operational management is at the level of states and provinces, there is no capacity to regulate. Also in both China and India, the tremendous numbers of groundwater users, large and small, confound regulation of groundwater. 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.~~ With sustainable management, there are significant burdens in needed technical knowhow, in collecting necessary data, and in funding advanced technologies. Thus, there are risks that that Iran, India and Pakistan will run short of groundwater from over-pumping in some places, and also be adversely affected by global climate change.

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 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 groundwater management and presents suggestions for a pragmatic research agenda.~~ Further, it describes governmental and socio-economic impediments to sustainable groundwater management, along with evident deficiencies in available data and for most, absent capacity to either regulate or undertake necessary projects. There is a huge gap between the full-blown blown water management approaches with demonstrated compliance, for example, in Singapore, and California, USA and those in Asia.

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.

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 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 at national levels, together 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. 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 use 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 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.

~~By rights,~~ Had decision makers acted on the basiss of scientific knowledge, 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. Yet, these ideas did not lead to substantive action because there was little in the way of operational frameworks and capacity for management.

2 ~~Few Signs of Progress and Worsening Trends~~ Trends in Depletion and Contamination of Groundwater Continue to Worsen

In China, India, Pakistan and other hotspots (Figure 1)~~, groundwater continues to be impacted by groundwater depletion and contamination.~~), 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~~ 4.9x10^4 km^{2}in the 1990s to 7.9x10^4 km^2 in 2000s to 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. ~~G~~For India, 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 > 200 m thick, 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 ~~r~~ restricted to certain local areas. ~~egionalized. Yet, w~~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~~ Often misunderstood, the threat to the sustainability of supplies from IGA aquifer system is 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., 201~~8~~7). Citing centuries of mismanagement of water resources, and "institutional incompetence" (Biswas et al., 201~~8~~7) in the context of a large growing population, there has been no willingness for action politically in India beyond "cosmetic changes" (Biswas et al., 201~~8~~7). 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., 201~~8~~7).

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 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 total 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 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, 2010). The most important limitation is that water is a state responsibility and many of the states in India have no capacity to monitor groundwater production or to 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 (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 best 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 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 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 water-level 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. 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. The challenge in this respect is in finding water sources for MAR.

The Asian countries we have examined also have problems with data. 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 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 more progress in China but information there is siloed and lacking in necessary transparency.

There are positive 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 streambed infiltration systems with millions more planned (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) and whether they can be effective without actions that manage demands and quantities pumped.

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 pavements or utilizing/storing storm water in rain gardens or rooftop gardens. These kinds of green infrastructure projects are growing in China. While contributing to groundwater sustainability through urban recharge, it is not yet clear what that contribution will be.~~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, 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. ~~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 on sustainability require expensive infrastructure with continuing operating costs, especially with the development of new water sources for MAR, for example, treated sewage, rainwater, or imported surface-water. 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~~ Clogging is a problem reducing the quantities of water infiltrated or injected into the subsurface, but can be managed with regular maintenance to maintain performance. 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.~~ Farmers in India (and China) prefer groundwater for irrigation as compared to government-supplied surface water (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)~~ Finally, more efficient irrigation technologies might lead to reduced pumping, while also leading to reduced recharge (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 is collected and treated conventionally, then purified 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 seawater 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 other 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 modern and reliable water/power infrastructures, and (iii) a manageable problem scope stemming from relatively small populations.

~~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):~~

~~$74\ Mm^3\ yr^{-1}{}_{NR} + 185\ Mm^3\ yr^{-1}{}_{IR} + 86\ Mm^3\ yr^{-1}{}_{ATW} - 345\ Mm^3\ yr^{-1}{}_{PGW} = 0$ (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~~ Groundwater Management: A Call to Action

There are compelling arguments ~~why it is unrealistic to expect groundwater to be managed sustainability in developing~~ to explain the slow development of a sustainability ethic in some 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.~~ For India and Pakistan, where operational management is at the level of states and provinces, there is no capacity to regulate. Also in both China and India, the tremendous numbers of groundwater users large and small confound regulation of groundwater. Thus, 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 prerequisite for problem understanding and management decisions remains a problem for all countries except perhaps China. ~~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.~~ There is, however, some hope that new technologies, may create sufficient visibility on the severity of the groundwater problems to finally spur action (Fogg, 2019). For example, there are relatively inexpensive, wireless technologies available for monitoring water levels in real time. Expected improvements in satellite-remote sensing, particularly future GRACE missions, are also expected to improve our understanding of aquifers worldwide (Fogg, 2019). However, field-based hydrogeological campaigns (e.g., MacDonald et al., 2016) and comprehensive water-quality monitoring will be necessary.

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 international researchers but with in-country collaborators and cooperators. Influential in this respect are long-term studies by The World Bank on specific strategies for management, large-scale interpretations of water storage changes with 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 with over-pumping (MacDonald et al., 2016). Problems of arsenic pollution are widespread including Pakistan, while human activities that have led to groundwater salinization and urban/agricultural contamination (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 in modeling and arid-zone geochemistry.~~ and a need for water-quality monitoring as an essential step for sustainable management. ~~For example, s~~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.~~

We hope that countries in Asia begin to address sustainability problems more aggressively in critical areas, including the practical hydrogeologic investigations needed to support complex projects. There is some thinking that after many decades of aggressively exploiting aquifers, societies have begun to wake up to the need to manage and recharge aquifers (Fogg, 2019). Yet, there is a significant risk that progress will be slow in many Asian countries given the problems of capacity and socio-economic constraints. ~~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~~ A major transition will be required to move from water policies, viewed widely as muddling along~~,~~ ~~stumbling~~ from one crisis to the next without substantive actions to full-blown projects with demonstrated compliance (i.e., Singapore, California). ~~to quantifiably sustainable systems, like those in Orange County or Singapore will be enormous. Further, it is doubtful whether the s~~Only time will tell, as to whether the successful ~~uccessful~~ ~~strategies~~ water management schemes in places with relatively small and economically advantaged populations are practically scalable to many tens-of-millions of people in developing countries. ~~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.~~ There are basic technical approaches that have the potential contribute to sustainability. For example, several countries are already invested in recharge projects, India with their tradition MAR (Davis et al., 2018) and China with their "sponge city" concepts. While, these approaches are represent an important first step to groundwater sustainably, they are no panacea. For example, tradition approaches to water harvesting in India are not well suited for hard-rock areas, impact downstream users, and often lead to more pumping (World Bank, 2010). In addition, there is significant uncertainty as to whether these approaches will contribute meaningfully to sustainability, especially with uncontrolled withdrawals. All of 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.

~~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.~~

There are risks that that Iran, India and Pakistan will run short of groundwater from over-pumping in some places and be adversely 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 examined the extent of in-country migration in order that countries "can plan and prepare" (Rigaud et al., 2018). The study involved modeling future 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 the threats associated with running out of groundwater. No doubt, such analyses would be difficult and uncertain, given absence of data. Yet, with potentially 100s-of-millions of people at risk, it would be prudent to better understand the scope and scale of future problems.

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.

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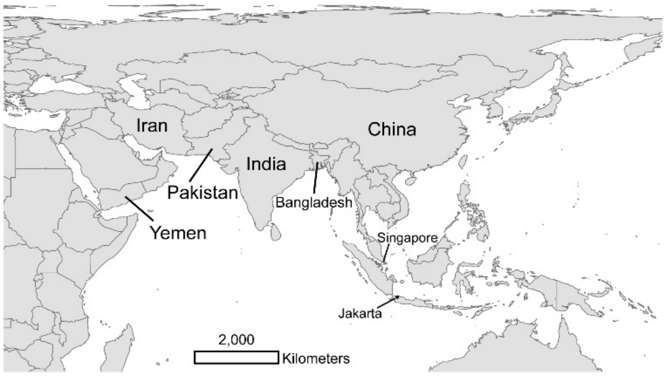


Figure 1: Map showing the Asian countries and cities discussed in the paper.

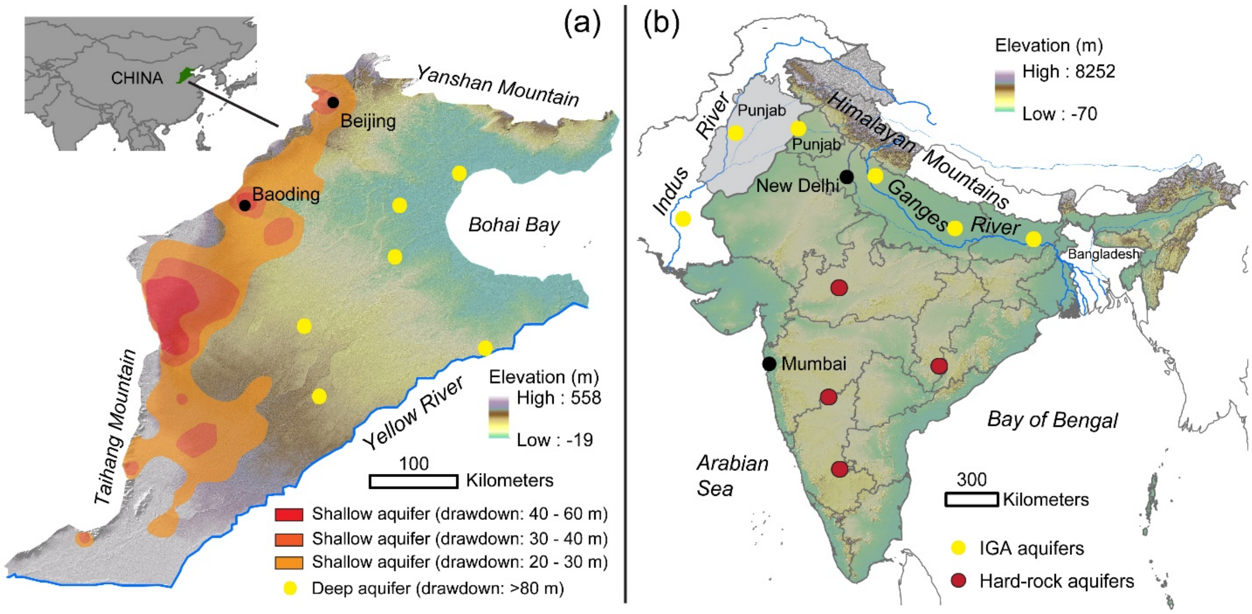


Figure 2: Panel (a) is a shaded relief map of the core of the North China Plain. The red/orange colored areas have drawdowns >20 m in the shallow aquifer (Cao et al., 2012). The yellow dots indicate areas with local drawdowns in the deep aquifer >80 m (Zheng et al., 2012). Panel (b) shows India, Pakistan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

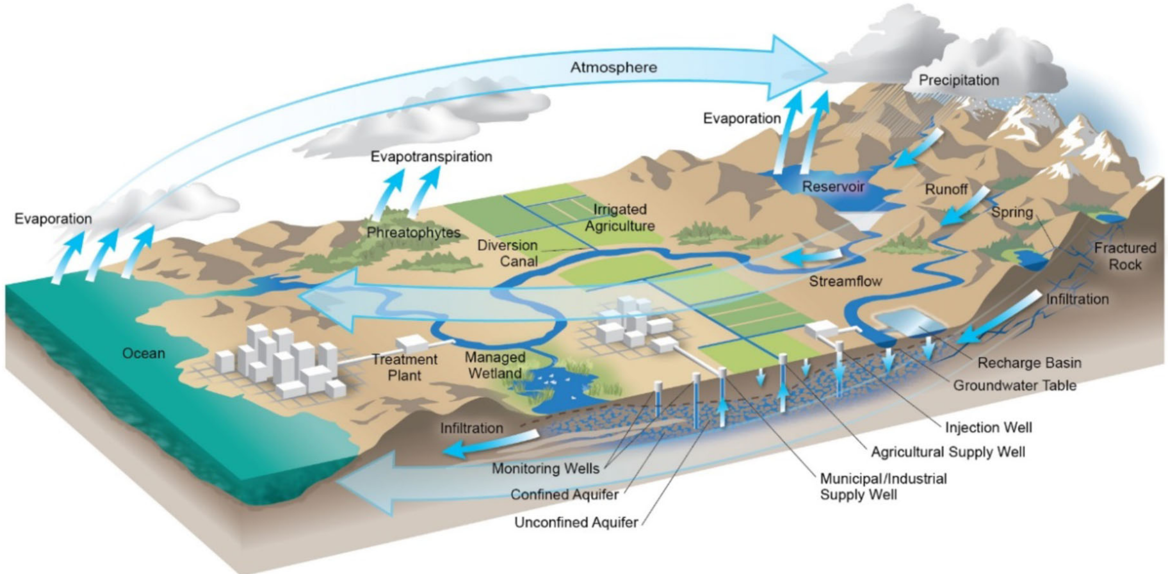
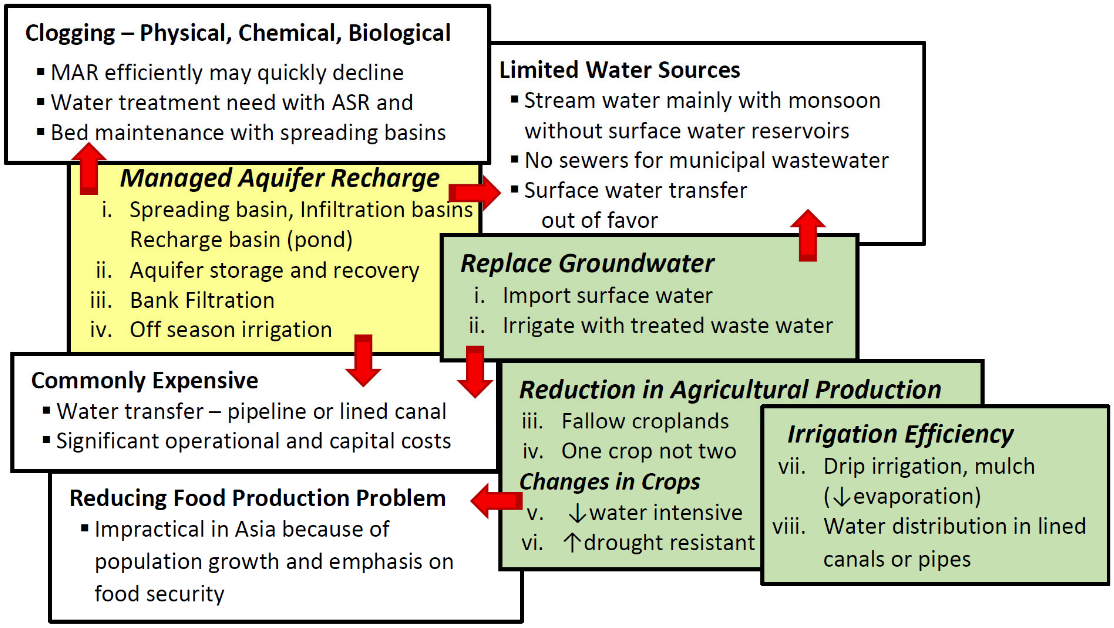
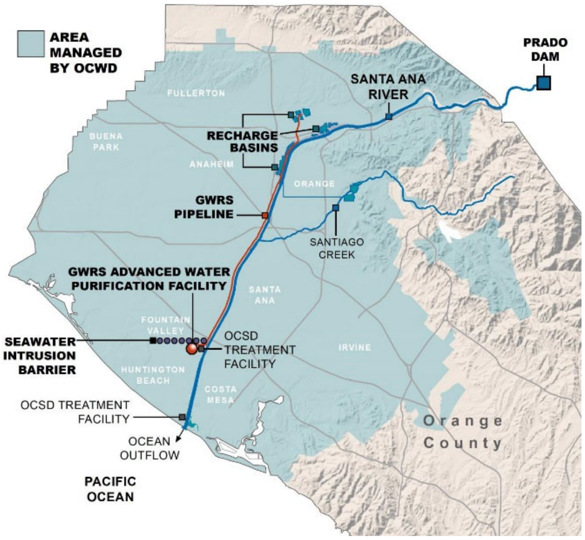


Figure 3: Conceptual model of a hypothetical coastal hydrologic system featuring a major river, cities, agricultural irrigation, an alluvial aquifer system being recharged using various MAR systems, and more. Complexities arise from (i) the number of different processes operating within the basin and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



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).**~~