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The water–food–energy nexus in Pakistan: a biophysical and socio-economic challenge

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Abstract. We draw on previous work examining historical trends, likely future water use and food availability in Pakistan and extend the analysis to consider interactions with hydropower generation and the energy demand in food production due to pumping of groundwater for irrigation. Business-as-usual scenarios suggest growing demands for groundwater and energy use for food production as population grows rapidly. However, groundwater use is already unsustainable in many areas, and energy supply is failing to keep up with demand. Quantifying material linkages between water, food and energy provides a means to explore biophysical constraints. Characterising institutional constraints is equally important, as they can be significant barriers to effective stewardship of water, energy and food resources. The experience in Pakistan reinforces this finding, and we discuss the implications for hydrologists.

1 Background

The water–energy–food nexus is conceptualised and analysed in many ways, with various authors offering generalizable insights. We consider some of these insights in relation to the Indus Basin in Pakistan.

Scott et al. (2015) considered that “resource recovery is the basic biophysical expression of the nexus approach”, and that biophysical limits ultimately require resource uses that do not externalise unwanted impacts. The authors emphasised resource linkages beyond a biophysical analysis to include materials, institutions and security.

Kirby et al. (2017) characterised the material linkages between water and food for three population growth scenarios in Pakistan, with a focus on one aspect of food security, food availability, and provided biophysical bounds and possibilities for the water-food system by exploring water use and crop yield assumptions. In this paper we extend the analysis to include material interactions with energy and, following Scott et al. (2015), anticipate beyond material linkages to consider institutional and security dimensions. “Security” here refers to “human and ecosystem dependence dimensions of resource security”. We include considerations of resilience and adaptive capacity.

2 The water–energy–food nexus in Pakistan

The population estimate for Pakistan is almost 190 million. From 1961 to 2013, population grew 3.8 times (UN, 2015), whereas grain production grew 5.2 times. Food availability has improved, but many people remain malnourished (Kirby et al., 2017). Increased food production was achieved by increased use of groundwater for irrigation, while diversions of surface water have remained unchanged. In 2007, about 77 billion cubic metres (bcm) of water was supplied from rivers, and 40 bcm from groundwater (Kirby et al., 2017). It is generally agreed that groundwater is overused in many areas, particularly in the Punjab, and continued use at this rate is unsustainable (Kirby et al., 2017) and risks non-recoverable expansion of saline areas.

Farm energy use is increasing faster than crop production. Groundwater pumping (mostly diesel) represents 60 % of agricultural energy demand (Siddiqi and Wescoat Jr., 2013).

Table 1. Material consequences of five categories of food-water activities and two energy options. Consequences are relative to Kirby et al. (2017) "yield only" scenario with median population projection.

Approach	Water perspective	Energy perspective	Food perspective
(1) Increase crop area and water use	Risk of higher water demand and of demand exceeding supply. Potential for irrigation demands to be affected by hydropower requirements.	Agricultural demand for energy is low relative to other sectors, but hydropower vs. irrigation tensions could be heightened under this option.	Higher crop production, with higher dependence on affordable and reliable water and energy supply.
(2) Increase yield per unit water; or (3) swap to lower water use crops	Potential to lower agricultural water demand, but only if system rebounds are managed.	Potential to lower agricultural dependence on energy supply, but only if system rebounds are managed.	Potential for same production with lower dependence on energy and water.
(4) Import more food, export less; or (5) slower population growth	Lower demand for irrigation water.	Lower agricultural demand for energy, and potential to ease tensions between hydropower and irrigation requirements.	Potential to ease demand for food from agricultural sector.
(6) More hydropower from (a) large dams and/or (b) local barrages	May help or hinder provision of irrigation water depending on dam locations and operations.	Improves energy supply. Option (b) may help build local supplies without large investment in new grid infrastructure.	Linked to water. May ease other barriers to food access (e.g. opening new livelihood options, more reliable cold storage).
(7) Import more energy	Relieves constraints that hydro places on irrigation water.	Increases dependence on affordable and reliable energy markets.	Linked to water. May ease other barriers to food access (e.g. opening new livelihood options, more reliable cold storage).

Although agricultural use of energy is only 2 % of total energy use (based on 2012–2013 figures from Ahmed et al., 2015), it contributes to demand for imported oil, exacerbating Pakistan's trade imbalance. The building of dams for irrigation increased availability of hydropower, but capacity and output have barely increased this century and electricity supply is regarded as in crisis (Energy Sector Task Force, 2010; Kugelman, 2015).

Population growth may reach 310 million by 2050 (UN, 2015), with associated demand for more food, water and energy. Kirby et al. (2017) suggested maintenance of adequate food availability will be via five approaches: (1) increased area and water use of food crops, requiring more water from over-used aquifers or more surface water storage; (2) increase in crop yields per unit of water (at greater rates than in the past); (3) swapping to crops with lower water demand; (4) exporting less food and importing more; and (5) slowing population growth, though this is likely to have only long-term impact.

These approaches represent statements of material assumptions rather than policy options: if by 2050, current food availability has been maintained, it will be through a combination of those five approaches, whether or not through planning and deliberation.

Decisions to increase energy supply can be made independently of water-food options, though there are clear interactions. Two energy options are: (6) build dams and hydroplants to supply more power (noting potential hydropower capacity is $> 54\,000$ MW, compared to the current 6500 MW; Energy Sector Task Force, 2010), and (7) importing energy (Sharma et al., 2004). Option (6) could come from a few large dams, requiring major transmission infrastructure, or from local distributed sources such as small scale hydropower on irrigation canals and at other barrages which are close to demand centres (Energy Sector Task Force, 2010). The electricity grid needs significant upgrading to meet existing demand, let alone to accommodate new hydro or transboundary supplies which bring extra challenges in financing, locating, building and maintaining very long transmission lines in difficult terrain.

Material nexus perspectives on water-food options

At 2 % of total demand, there is little risk of agricultural energy demand impacting on national energy availability or prices. But high energy dependence means the agricultural sector is heavily impacted by energy prices, availability and reliability. In relation to hydropower and groundwater pumping, the five approaches of Kirby et al. (2017) have clear material implications for water, energy and food. Table 1 shows these impacts relative to the "yield only" scenario, where crop yields increase according to historical trends, but areas do not change. The first approach tightens coupling in the water–energy–food nexus by placing more demands on limited water resources. Crop production will have higher energy demand for groundwater pumping, and river operations will need to balance hydropower and irrigation requirements.

Approaches 2 and 3 can save water by lowering demand by efficient use (via irrigation practices and technology, improved yields and growing crops with low water-demand). Ahmad et al. (2014) found savings from efficiency measures at the farm-scale did not translate to savings at the basin-scale. One reason for this is because of system "rebound": local efficiency gains are consumed in other ways, leading to no system-scale saving (Scott et al., 2014). For example, increased efficiency enables farmers to increase land area under production for the same water use. In the absence of a basin-level cap on diversions, basin-level water use would increase until biophysical limits are reached. Thus approaches 2 and 3 would require political agreement, regulation and compliance for basin-scale diversion limits.

Approaches 4 and 5 could relieve tensions by reducing demand for food, energy and water, but there are limitations. For example, approach 4 implies structural transformation of the economy, conflicts with political-cultural preferences, and financing options are unclear. For approach 5, the population would continue to grow even if there was a large decrease in fertility now. These two approaches are not in the mandate of authorities responsible for water, energy and agriculture.

3 Potential nexus solutions

Nexus solutions have focused on large infrastructure such as hydropower dams and new irrigation schemes. Three large hydropower dams each with over 1000 MW installed capacity currently supply 80 % or more of Pakistan's hydropower of about 7000 MW (Private Power and Infrastructure Board, 2011). There are approximately 60 irrigation schemes on the Indus and its tributaries, with a total command area of about 18 million ha, making it the world's largest contiguous irrigation area (Archer et al., 2010). However, such projects face major challenges. International donors are reluctant to finance dams and storages designed only for irrigation. Dam projects are proposed in provinces of Gilgit-Baltistan and Azad Jammu Kashmir, in territory disputed with India, and require agreement from India to arrange international financing. The Kalabagh dam, not in disputed territory and which banks are willing to finance, is not supported by the government of Sindh province.

Large-scale irrigation efficiency is called for as a solution via delivery of easily-realised, readily acceptable gains. But, as discussed above, net efficiencies may be much lower than anticipated (Ahmad et al., 2014; Scott et al., 2014). Other, local, solutions may be politically more achievable: small-scale hydropower at head works; improved irrigation efficiency in well-identified places; improved water delivery; and managed aquifer storage to keep groundwater tables higher and reduce energy use in pumping. The private sector has an important role in small hydropower, as evidenced by projects in Khyber Pakhtunkhwa and Gilgit-Baltistan. However, projects on headwork/canal networks require endorsement by provincial government irrigation departments.

Our overview has been framed by the biophysical limits assessed by Kirby et al. (2017). However, it is clear the water–energy–food nexus is also characterised by institutional limits, which manifest differently according to the five approaches (Table 1). These include operational limits to manage a tightly-coupled nexus that maximises water, energy and food outputs, and limited socio-political capacity to create and implement basin-level solutions beyond the mandate of individual energy, water and agricultural authorities.

Such socio-political factors tend to be considered out of scope for biophysical scientists, other than in calling for "good resource governance". By so doing, biophysical scientists risk distancing themselves from implementable solutions that take them beyond specific domain knowledge and expertise, or the mandate of their organisation.

4 Alternative nexus perspectives

Mindful of this risk, we review nexus perspectives that include institutional and security considerations as a step towards addressing the need "to acknowledge the existence and legitimacy of a range of narratives and frames in pursuing a nexus approach" (Middleton et al., 2015).

One difference between nexus approaches is in how they treat agency. A resource efficiency approach, as applied by Kirby et al. (2017) and Laghari et al. (2012), presents technical means to maximise productivity within biophysical limits, but is silent on issues of actors and their agency (other than perhaps an unspoken assumption that compelling resource analyses will motivate government policy for change). Resource efficiency approaches acknowledge the need for policy and practice reform but focus on technical solutions to increase synergies and reduce trade-offs between supply and demand relating to water, food, energy and environment.

A critical social science perspective focuses on the power relations and societal structures that shape and reinforce resource-access tensions. Akhter (2017) considered "access to land … is arguably a much more relevant factor for evaluating water and food security than the total amount of water available", referencing estimates that 2 % of householders in the Indus Basin own almost half the land area. Social relations are key in shaping resource access options for different social groups, as evidenced by steep increase in rural landlessness associated with unequal distribution of the benefits of increased agricultural production: an outcome of the Green Revolution was concentrated land ownership for the few and reduced incomes and livelihood security for a significant proportion of the population. A critical social science perspective emphasises the need to reform deep inequities that represent limits as least as powerful as biophysical constraints.

Another way nexus approaches differ is in stakeholder engagement. A spectrum exists from participatory, multi-scale, multi-stakeholder resource management (commonly recommended, but rarely realised) to restricted participation by actors from state agencies with formal responsibilities for water, energy and agricultural sector planning and service provision. A third way nexus approaches differ is how questions of resilience, adaptation and transformation are addressed. At one end of the spectrum is maximising resource efficiencies and production; at the other efficiency and production are considered in light of natural disasters, system tipping points, rapid global change and shocks. Allouche et al. (2014) found current dominant nexus solutions were framed by "stability" and "durability", even though "clumsy solutions" involving exchange of differing world-views and problem perceptions were more appropriate for water–energy–food nexus dynamics.

For example, small-scale hydropower will not "solve" water–energy–food challenges in Pakistan, but have desirable attributes: they use existing barrages; do not require large investments in long-distance transmission lines; are well suited to limited electricity grids and raise fewer social-political concerns than large hydro projects. Two of the authors (GP and MA) developed a river system model for the Indus with multiple stakeholders familiar with complex river operations and the social-political decision context. By learning about the potential for small hydropower developments, new questions were addressed with the river system model, and new criteria were developed against which model scenarios could be assessed. Early indications are that including energy considerations brings potential benefits to water users. Barrages need maintenance that would be hard to fund if benefits were only to irrigation. A stronger case can be made if energy supply options are included, as well as safety and livelihood impacts of infrastructure failure.

This example is consistent with key messages of Allouche et al. (2014, 2015) that emphasise recognition of institutional limits, working with diverse kinds of storage and using pluralism to achieve "many ten percent" solutions. These may not be optimal from any single perspective, but are judged as acceptable according to a diverse range of perspectives and are thus more practical and effective than other solutions.

5 Conclusion

In the Indus basin, the biophysical limits of the water–energy–food nexus are just one piece of the picture. Characterising the material linkages is helpful for diagnosis, and for developing a testable evidence base for assumptions and hypotheses about the material consequences of different interventions. These approaches are useful because they provide insights independent of social and historical context to reveal commonalities that stakeholders can agree on, despite other differences. This approach was vital to the successful negotiation of the Indus Waters Treaty between Pakistan and India (Gulhati, 1973).

It is valuable to recognise, however, that in the Indus basin and elsewhere the water–energy–food nexus can be understood through critical social science and resilience or adaptation-oriented perspectives. Rather than alternative perspectives being at odds with biophysical analyses, or imposing constraints on solutions, these approaches can expand options usually considered out of scope for biophysical scientists or water, energy and agricultural authorities. For biophysical scientists engaging with the nexus, a willingness to include diverse perspectives presents new opportunities. On a technical level, it can reveal new questions to ask of biophysical models, and inform exploration of model scenarios to make analyses relevant to a wider social-political context.

Respectful humility and awareness of the limits of our knowledge helps bound us to our disciplinary training and experience. Being open to alternative perspectives requires suspension of judgment and time devoted to seeing a familiar situation with genuinely new eyes. Such re-framing is challenging because it represents a different way of engaging with the world and embracing uncertainty, ambiguity and scope-creep of dynamic, distributed "clumsy solutions" rather than pursuit of certainty and control. The capacity to re-frame also requires alternative perspectives to be held in juxtaposition to uncover insightful intersections or conflicts between them (Roe, 2012; Foran et al., 2014). In Pakistan the Vision 2025 Agenda and the Government of Pakistan's commitment to the Sustainable Development Goals could provide potential platforms that would support a broader range of perspectives than usually possible within sector-bound agencies.

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