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ORIGINAL ARTICLE

Can Pakistan achieve sustainable water security? Climate change, population growth and development impacts to 2100

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Abstract

We use an integrated population–GDP–food–water model to examine development scenarios for Pakistan relevant to food and water security. The scenarios include as follows: base case (business as usual), population growth; economic growth; wealth inequality (which affects population growth, economic growth and food demand); agricultural yield increases; impacts on water availability of storage dam construction, sedimentation in storage dams, and desalination; and impacts on water availability and crop water demand of climate change. The results indicate that the water security outlook for Pakistan is likely to worsen in coming decades, and groundwater demand for irrigation is likely to increase. However, in the second half of the century, the combined effects of slowing population growth and increases in crop yields could see the situation start to reverse, with decreasing demands for groundwater for domestic food production. While some scenarios, such as a higher rate of population growth or lower rates of yield increase, lead to a worsened water security outcome, others lead to greater water security. Combining several strategies to reduce water demand leads to greater future water security and sustainable water use in Pakistan. However, there may be trade-offs amongst sustainability goals. Climate change impacts on water availability are uncertain, and may lessen or exacerbate water security challenges.

Keywords Integrated model · Water security · Groundwater demand · Population growth · Economic growth · Pakistan

Introduction

Many developing nations face challenges with increasing population, growing demand for food and hence irrigation water, and unsustainable use of water. At the same time, they seek to increase economic development to tackle poverty, implying an even greater use of resources in general and water in particular (Boretti and Rosa 2019). Groundwater use globally is particularly important, and its use may involve trade-offs amongst sustainable development goals, such as protecting groundwater on one hand and food security on the other (Velis et al. 2017).

Pakistan already experiences a low availability of water per capita, with groundwater use commonly regarded as unsustainable (Kirby et al. 2017). Population growth, with consequent growth in food demand and hence increasing demand for water for irrigation, will present great challenges in the future (Kirby et al. 2017). Whereas climate change will increase crop water demand, the impact on water availability is less certain, with increases or decreases possible (Ahmad et al. 2021). Solutions to this dilemma include supply management options, such as new storages (Water Sector Task Force, 2012), sedimentation management (Khan et al. 2012; Roca 2012; Raza et al. 2015), desalinization of saline sea- and groundwater (Kumar et al. 2018), improved canal water management (Mekonnen et al. 2016), and conjunctive use and managed aquifer recharge (Arshad et al. 2020). Demand management options include improving crop yields, growing a smaller area of high water using crops, such as cotton, sugarcane and rice, and greater areas of lower water using (and more nutritious) crops, such as legumes (Kirby et al. 2017).

Tackling such a complex issue is aided by the application of models that integrate the many aspects. The Indus

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Basin Model Revised (IBMR) has been used to investigate impacts of climate change (Leichenko and Wescoat 1993; Yang et al. 2014, 2016), crop pricing policy (Hai 1995), salinity management (Rehman et al. 1997) and raising the Mangla Dam (Alam and Olsthoorn 2011). However, the IBMR does not deal with population growth, nor aspects of the wider economy, such as GDP growth, and the export/import of crops or foods.

The CGE (Yu et al. 2013) and CGE-W Young et al. (2019) are computable general equilibrium models of the Pakistan economy that simulate the impact on the Pakistan economy of a change to water availability. Yu et al. (2013) used the CGE model to study several scenarios, including climate change, new storages and improving crop technologies and yields. Young et al. (2019) and Davies and Young (2021) used the CGE-W model to analyse water security trajectories in Pakistan under several scenarios. Davies and Young (2021) found that without critical reforms, water demand could easily exceed supply by 2055, whereas with reforms Pakistan can ensure food security and achieve middle-income status by 2050.

A WEAP model of the Indus Basin has been used to analyse the impact of population growth on water demand (Hassan et al. 2019), and potential management responses, including reservoir operations (Rafique et al. 2020). This model does not include food security or economic aspects.

The above models are all intensive numerical models with a detailed representation of the hydrology of the Indus Basin. They require considerable time and effort to obtain the relevant input data and to set up and run scenarios, and yet do not include key aspects of food and water security. In contrast, Kirby (2021) presented a simpler, though more wide-ranging, model of the interactions amongst population, GDP, food demand, agricultural production, water availability and water use in Pakistan, where the water availability is based on the Indus Basin as a whole.

Our aim here is to examine development trajectories of water demand to 2100 for Pakistan under a range of assumptions about future development and climate change. In particular, we seek to examine whether groundwater can be used sustainably. We use the model of Kirby (2021) and include the effects of population growth; economic growth; wealth inequality (which affects population growth, economic growth and food demand); agricultural yield increases; impacts on water availability of storage dam construction, sedimentation in storage dams and desalination; and impacts on water availability and crop water demand of climate change. In the model, population growth, economic growth and wealth inequality are linked, and co-evolve in a way which matches the observed development in Pakistan from 1960 to 2020, and the expected development in the future (Kirby 2021).

The novel contribution in this paper is the range of effects considered under a single integrated analysis, in particular the integration of supply and demand (including climate change impacts) with socio-economic effects of population growth, wealth inequality and GDP growth. We also consider projections to 2100, which is further ahead than most studies (e.g. Kirby et al. 2017, who assessed projections to 2050; Davies and Young 2021, who considered projections to 2055). This leads to a key finding that in the second half of the century the water outlook for Pakistan under some plausible scenarios could become progressively more optimistic, in contrast to the often pessimistic outlook to 2050 (e.g. Kirby et al. 2017).

Methods

Integrated model of population growth, GDP growth, food supply and water security

The model was fully described in Kirby (2021). Briefly, the model incorporates all the effects shown schematically in Fig. 1. It uses ideas from the unified growth theory, a long-run development model of population and GDP growth due to Galor (2010), which also incorporates the effects of inequality. The GDP growth aspect of the model is augmented by a three-sector economy approach, based on production functions, similar to that taken by Yokomatsu et al. (2020) to examine the impact of drought in Pakistan. The model includes the split of the population into rural and urban sectors.

The population demands food (with poor people demanding less and wealthy people demanding more), which is supplied by major crops. Cotton is grown for export. As the population grows, so too does the food requirement, and hence the area of crops to be grown. The demand for food rises further with increasing per capita wealth. As the economy and per capita wealth grow, the rate of population growth slows, in line with observed and expected behaviour (Kirby 2021). Crop yields also increase with time. Crop production and water demand are based on the widely used crop coefficient approach of Allen et al. (1998), in which the crop coefficients are multiplied by reference crop evapotranspiration to give actual evapotranspiration, with the resulting water demand linked to a simple river basin model. The model divides the Indus Basin into four catchments (Upper Basin East, Upper Basin West, Mid Basin, Lower Basin) which receive monthly precipitation, temperature and reference evapotranspiration based on measured records. The model includes snow and glacier dynamics in the upper catchments, which leads to features, such as reduced snowmelt with climate change. In a warmer climate there is an increase in the fraction of precipitation falling as rain, and a reduction
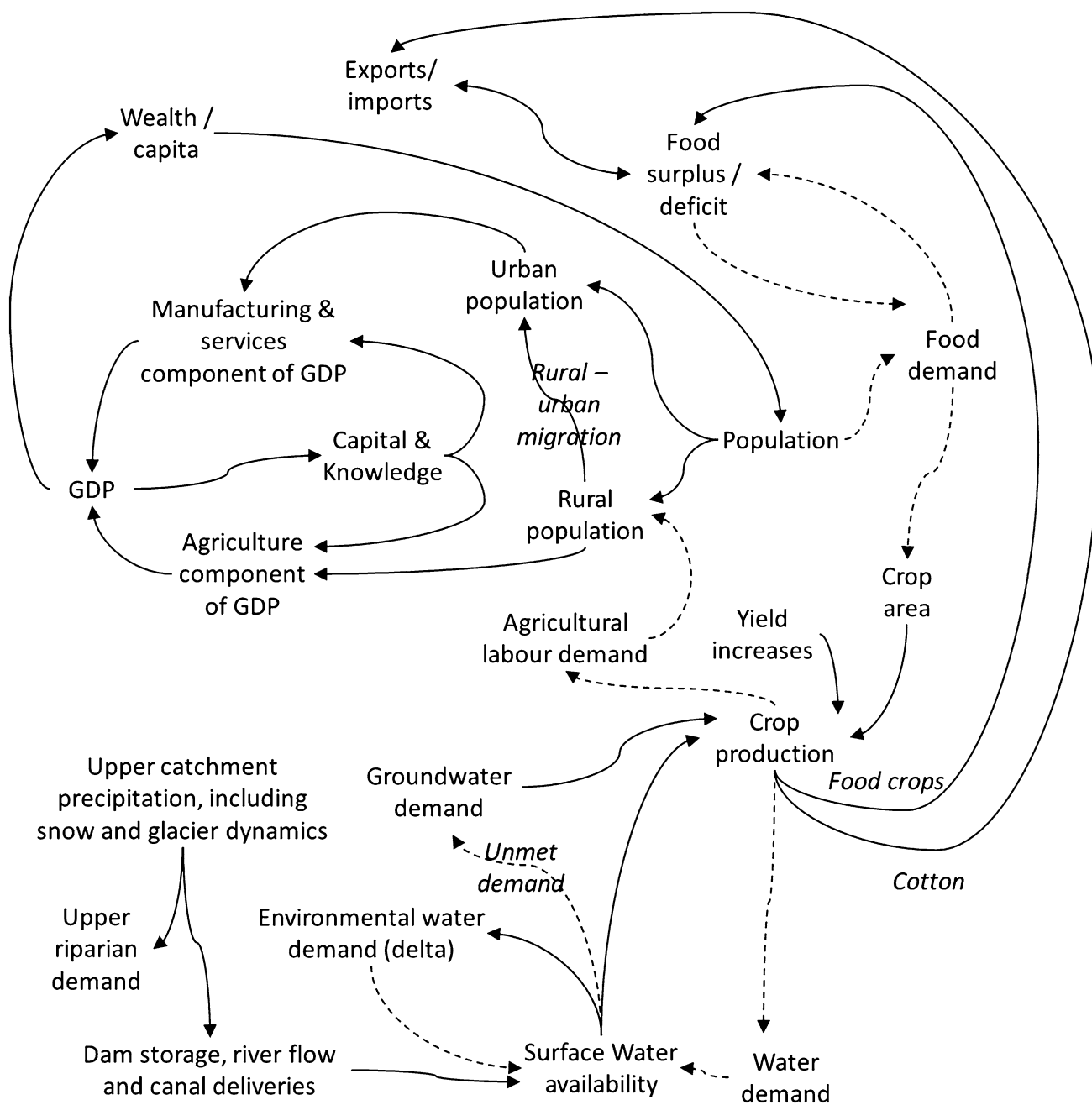
Fig. 1 Schematic diagram of the integrated population–GDP–food–water model. Dotted lines indicate a demand

in the fraction precipitation falling as snow, which reduces snowmelt. Glacier melt similarly responds to temperature changes. Much of the flow from the Upper Basin East is used for irrigation before it reaches Pakistan. This use grows in proportion to the demand in Pakistan. The basin model incorporates a single storage dam to simulate the combined capacity of Tarbela and Mangla, the main storage dams that supply irrigation water in Pakistan, and includes sedimentation of the water storage. The model has provision for a minimum flow to the delta which, if required in a scenario, is

supplied provided that there is sufficient water to do so. The model assesses the residual irrigation water demand after the supply from the surface water resource, as influenced by storages and minimum flow provisions. The residual demand has historically been satisfied by groundwater use. Kirby et al. (2017) pointed out that despite concerns over unsustainable use of groundwater, Pakistan has for some decades used ever more groundwater to supply an ever-larger area of crops, with no sign of the trend abating. The consequent food production at the national level is adequate and per

capita availability has increased over time, though with considerable inequalities in distribution (Kirby et al. 2017). The model is consistent with this behaviour.

Kirby (2021) showed that the model can simulate reasonably well the historical (1960 to present) evolution of a wide range of features of Pakistan, including population growth (with urban and rural population split); wealth inequality; GDP growth (overall and in the agriculture, manufacturing and service sectors); the areas, yield and production of 7 main crop types in the mid and lower basins (broadly, Punjab and Sindh respectively); food availability, export and import; surface water availability, river flow and irrigation diversions in the Indus Basin, split into two upper, a mid and a lower catchment; and groundwater demand. The model also simulates future trends that compare with other projections (Kirby 2021).

Scenarios

We assessed projections under a base case (business as usual) and with changes which might result from socio-economic effects (changes to population growth rates, GDP growth rates and wealth inequality), agricultural and water management (crop yield increase, reducing areas of a high water using crop, new dam storage, storage sedimentation control, changing environmental flow reserves, desalination water supply), and climate change.

Base case

The base case is a simulation of the development of population, GDP, food supply, and water supply and demand in the absence of climate change or other changes. This business-as-usual scenario shows the impact on groundwater demand of crop yields continuing to increase at the historically observed rate balanced against population growth, which slows to zero just before 2100, changing diets, and the declining storage with continuing sedimentation. The climate for the base case is the historical climate time-series (of precipitation, potential evapotranspiration and average temperature) from 1960 to 2018, repeated from 2019 and then again from 2077. The base case is nearly identical to the example given in Kirby (2021), except that the simulation is run to 2100, rather than 2050.

Climate change

The World Bank Climate Knowledge Portal (https://climateknowledgeportal.worldbank.org/download-data) provides summary climate change information by country for 16 global circulation models and several emissions scenarios. We used the information to derive the 10th and 90th percentile climate change projections of the change to precipitation and average temperature in the period 2080–2099, for the RCP8.5 emissions scenario. The combination of two precipitation and two temperature projections gives four scenarios: hot-dry (10th percentile precipitation change/90th percentile temperature change), hot-wet (90th/90th), warm-dry (10th/10th) and warm-wet (90th/10th). The model also requires the input of potential evapotranspiration, for which the World Bank summaries do not give any information. However, Ahmad et al. (2021) derived climate change scenarios in which the changes to potential evapotranspiration varied from a modest increase, to a larger increase that in percentage terms was about 2/3 of the percentage change to precipitation in an extreme wet scenario. We used this as a simple rule for changes to potential evapotranspiration. Based on the foregoing, the four climate change scenarios are shown in Table 1. The projected changes in Table 1 were assumed to be those that would be obtained in 2100; the changes were applied linearly from zero in 2020 to the full change in 2100. The changes were applied to the rainfall, temperature and potential evapotranspiration of the base case for each of the four regions in the model.

The above procedure is a simple definition of projected climate change, and is applied via a simple hydrology model. However, we will show in the discussion section below that the results are not dissimilar to those of the sophisticated treatment by Ahmad et al. (2021).

Water storage increase

The volume of the water storage dam in the model at the start of the simulation (1960) is 25 billion cubic metres (bcm) in the base case (although the volume is progressively decreased by sedimentation). 25 bcm is approximately the combined initial capacities of Tarbela (Khan et al. 2012), Mangla (Raza et al. 2015) and the Chashma Barrage live storage component (Ali and Shakir 2018). The increased water storage scenario increases this to 35 bcm in 2030 (allowing time for implementation). There are various suggestions for increased water storage (e.g. the

Table 1 Four projected climate change scenarios, with the changed climate values in 2100

Scenario	Precipitation change, %	Potential evapotranspiration change, %	Average temperature change, °C
Hot-dry	− 10	20	5
Hot-wet	30	20	5
Warm-dry	− 10	5	3
Warm-wet	30	5	3

Water Sector Task Force 2012) which, if all implemented, would amount to a greater volume than assumed here.

Water storage sedimentation decrease

The volume of the water storage dam in the base case is progressively decreased by sedimentation, at a rate of 0.5% of the original volume per year. This is an approximation of the rate in Tarbela (Khan et al. 2012; Roca 2012; Podger et al. 2021) and the slower rate in Mangla (Raza et al. 2015; Khan et al. 2020; Podger et al. 2021). The sediment rate suggested by these analyses varies, with lower rates given in the later works by Khan et al. (2020) and Podger et al. (2021). Khan et al. (2020) pointed out that catchment management has reduced sedimentation rates into Mangla. Archer et al. (2010) considered that sedimentation of water storages is likely to have a greater impact on future water availability in the Indus than will climate change. Ahmad et al. (2021) also showed that sedimentation will have a large impact particularly in Sindh and Balochistan. Reducing sedimentation rates is therefore a key consideration. In the reduced sedimentation scenario, the sedimentation rate is reduced to 0.05% of the original volume from 2030. We will show that the results of the changed sedimentation rate are not dissimilar to those of the sophisticated treatment by Ahmad et al. (2021).

Changed flows to the delta

In the base case, 1 bcm each month (if it is physically available) is reserved as an environmental flow to the delta, and is not available for irrigation. This is about the same as the 10 million acre-feet (12.3 bcm) suggested by Sindh as a minimum flow requirement in the 1991 Water Apportionment Accord (Government of Pakistan 1991). However, in many years, insufficient water is available in the model for the environmental flow reserve in the low flow months (see Fig. 23 of Kirby, 2021). In a reduced environmental flow scenario, the reserve is removed from 2030, and all water is available for irrigation. In an increased environmental flow scenario, the reserve is doubled to 2 bcm per month in 2030.

Desalination as a water supply

Desalination may in the future become a cost-effective source of water in the Indus (Laghari et al. 2012; Wada et al. 2019). Desalination could be regarded as a substitute for outflows in the delta; instead of cutting delta outflows, desalinated water could be provided. Therefore, we do not simulate a separate scenario, but regard the environmental flow reduction scenario as interchangeable with a desalination scenario of the same volume, starting in the same year.

Changed agricultural production

Three scenarios simulate changes to agricultural production. In the base case, the yields are assumed to increase by a constant amount (which varies amongst the seven crops and crop types) each year. In a lower yields increase scenario, yields are simulated to increase each year from 2021 at half the base case rate. While we do not invoke any particular causes for lower yield growth, we note that climate change is suggested to adversely impact crop yields (Kirby et al. 2017 and the references therein). In a higher yields increase scenario, yields are simulated to increase each year from

Table 2 Crop yields in 2100 for the higher yields increase scenario, compared to current potential yields

Crop	Current (2020) yields (T/ha) in the model	Yield (T/ha) in 2100 under higher yields increase scenario	Current potential yield[a] (T/ha)	References
Wheat	2.5	5.9	7.7	AARI (2020)
Cotton	0.8	2.1	3.8	AARI (2020)
Rice, coarse	2.0	4.5	12.7	AARI (2020)
Rice, fine			7.2	
Sugarcane	67	130	110 (130)[b]	AARI (2020)
Other cereals	2.0	4.6	10[c]	AARI (2020)
Pulses and oilseeds	0.5	0.5	2.8–3.8[d]	AARI (2020)
Milk	16	44	30–60[e]	Valentine et al. (2009)

[a]The current potential yields are those given by a regression line fitted through the data of potential yield vs date of introduction of the variety of the crop in question, given by AARI (2020)

[b]The most recently introduced variety has a potential yield of 130 T/ha

[c]Only maize is listed by AARI (2020)

[d]Several pulses and oilseeds are listed by AARI (2020), with the range of potential yields shown

[e]Valentine et al. (2009) gave a figure for Australian irrigated farms in 2009. It includes grain feed as well as pasture; however, the integrated model includes losses from wheat and other crops to various sources, including animal feed, and so is implicit in the model

2021 at double the base case rate. This higher rate of yield increase results in yields in 2100 which are somewhat less than current (2020) potential yields (Table 2). Broadly similar figures were given by Aslam (2016), except for sugar for which a figure of 300 T/ha was quoted. Given that all the crops listed by AARI (2020) show increases with time in potential yields (thus the potential yields will be greater in 2100 than currently), the assumptions used here are plausible. AARI do not list a potential milk yield from irrigated pasture, so Table 2 shows instead the milk yields achieved from irrigated pasture in Australia (Valentine et al. 2009).

The final agricultural production scenario is based on the suggestion in many papers (see Kirby et al. 2017) of reducing the production of cotton, rice and sugarcane, all high water using crops. For simplicity, we modelled the reduction in the area only of cotton, but the scenario can be considered as a partial reduction in the area of all three crops. In this scenario, the area of cotton is progressively reduced from its 2020 value to zero in 2100.

Changed rate of population growth

The rate of population growth in the base case is that which simulates the population growth to 2100 of the median projection of the UN (2019a). The rate of population growth from 2020 onwards was changed in two scenarios, one of which resulted in a 14% larger population in 2100, and the other of which resulted in a 16% lower population.

Changed rate of GDP growth

The rate of GDP growth from 2020 onwards was changed in two scenarios, one of which resulted in a 14% larger population in 2100, and the other in a 9% smaller population in 2100. Note that while a GDP change results in a population change, it also impacts other factors, such as food demand (a wealthier population has a higher food demand), so these scenarios are not direct substitutes of the population change scenarios above.

Changed wealth distribution

Although the impact is debated, poverty is often cited as a factor undermining economic growth (Sinding 2009). Sinding (2009) regarded recent evidence as conclusive, reducing poverty leads to lower birth rates, which in turn contributes to economic development. Tahir et al. (2014) and Afzal et al. (2012) found that poverty and GDP growth are associated in Pakistan. Consistent with these findings, changing the wealth distribution in the integrated model changes the rate of population increase (Kirby 2021) and also affects the demand for food (wealthier people demand more food and also a changed mix of food types, for example, with a greater proportion of

milk in the diet). The distribution of wealth was changed from 2020 onwards in two scenarios. In the first scenario, wealth was progressively distributed less equally, such that by 2100 the Gini coefficient was 0.45, up from its base case value of 0.31. In the second, wealth was progressively distributed more equally, such that by 2100 the Gini coefficient was 0.18. We will comment on the plausibility of these assumptions in the discussion below.

Combined scenarios

In the results to follow, we will examine the impact of each of the preceding scenarios in isolation. We then combine some of the scenarios to examine how well Pakistan could ensure water security to 2100 in the face of climate change. We combine only scenarios which have a large impact on improved water security, in combination with the most extreme wet and most extreme dry climate change scenarios. We compare the scenarios to the base case and the hot-dry and warm-wet scenarios as defined above. The combined scenarios are as follows:

1. hot-dry and warm-wet climate change plus increased crop yields (as defined above);
2. adding to the previous combined scenario the impact of a reduced area of high water using crops;
3. adding the impact of increased water storage;
4. adding the impact of decreasing delta flow/desalination water supply;
5. adding the impact of sedimentation control in the water storages;
6. adding the impact of a reduced rate of population growth and an increased rate of GDP growth.

In all cases except 6, the added scenario is as defined in the individual scenarios above. In the model, population and GDP are interdependent and co-evolve. It is not useful to combine the population and GDP growth scenarios as defined above, since this interdependency would lead to an extreme reduction in population growth. In combined scenario 6, therefore, we set the reduced population growth rate at half that specified above, and the increased GDP growth rate at half that specified above.

The final combined scenario is a worst-case scenario, in which the hot-dry climate is combined with an increased rate of population growth/decreased GDP growth, and a reduced rate of yield increase. In contrast to the six combined scenarios above, this leads to increased demand for groundwater relative to the base case and serves to show what Pakistan should seek to avoid.

Results

The integrated model results in the output of many variables, each as a time-series from 1960 to 2100. These include population, GDP, wealth distribution, food production, crop yield, areas of crops, demand for irrigation water (both surface and groundwater), surface water availability and river flows at several points in the basin (Kirby 2021). Here we focus on the time-series of groundwater demand as an indicator of water security, and on the population and GDP per capita (as an index) in 2100.
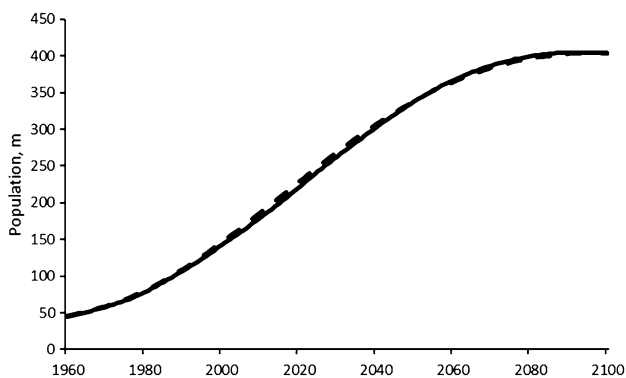
Base case

The population from 1960 to 2100 in the base case is shown in Fig. 2. The simulated population growth is similar to the median projection of the UN Population Division (2019a).

The demand for groundwater for irrigation in the base case (i.e. business as usual water management and use) is shown in Fig. 3. A key feature of the simulation is that groundwater demand is simulated to peak in about 2055, after which it declines. This feature arises because of the projected slowing of population growth shown in Fig. 2, and the projected continually rising yields. The fitting of polynomials, as shown in Fig. 3, is used as the basis for the scenario comparisons described below.

Groundwater demand in the scenarios

Figure 4 shows the groundwater demand in all scenarios, with like scenarios grouped in the plots in the figure. The base case result is shown in each plot as the solid line. The lines shown are polynomial fits similar to the fit for the base case shown in Fig. 3, with the base case fit to 2020 (or 2030 for the storage volume increase, sedimentation reduction and
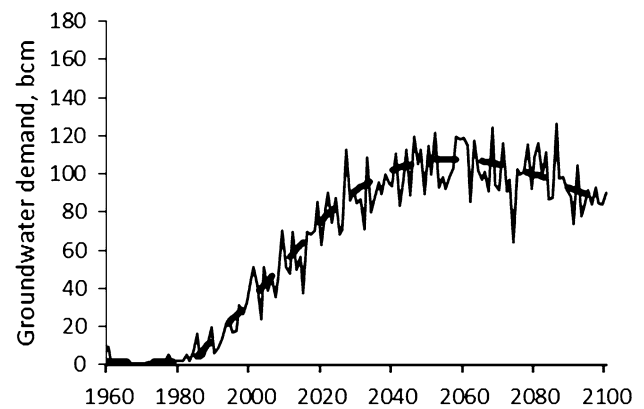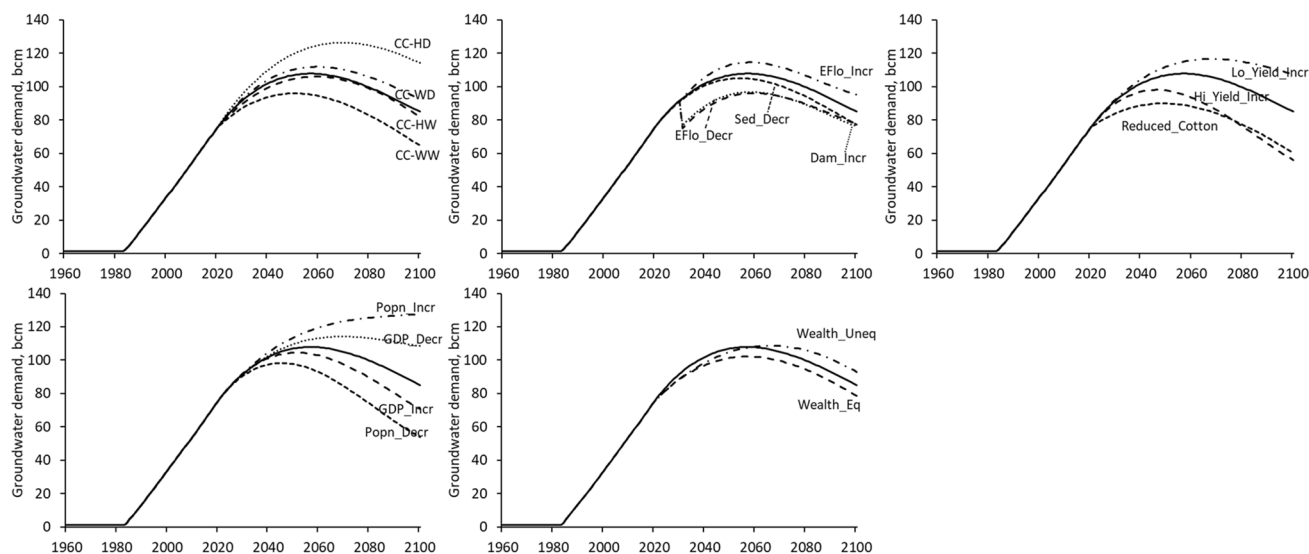

Fig. 3 Demand for groundwater simulated in the base case (solid line). A best-fit polynomial of the form $Y = a_1 + a_2X + a_3X^2 + a_4X^3$ is also shown (dashed line)

environmental flow scenarios) being used in each scenario, and the polynomial fit used from 2020 (or 2030) onwards.

The best-fit polynomial lines for the scenarios all rise above or below the base case line depending on whether the scenario results in a lesser or greater supply of water (for example, with more dam storage or less sedimentation in the second plot), lesser or greater demand for water (for example, with increasing or decreasing population, or decreasing or increasing GDP in the fourth plot), or a combination (in the climate change scenarios in the first plot). In the period to about 2055 (depending on the scenario), groundwater demand rises in all scenarios except the increased storage capacity and the environmental flow reduction/desalination scenario. As shown by the storage and sedimentation scenarios, changes in surface storage lead to an opposite change in groundwater demand. These three scenarios all assume additional supply is available for irrigation from 2030 onwards. While we do not evaluate alternative storage or desalination scenarios, other assumptions, such as a later implementation, would clearly shift the impact shown in Fig. 4 to a later date. Note that the delta flow reduction (environmental flow decrease) scenario (labelled Eflo_decr in Fig. 4) is also the desalination scenario (as explained in Sect. 2.2).

Population and GDP per capita in 2100 in the scenarios

The simulated population and GDP per capita results in 2100 are shown in Table 3. In all scenarios, where the population is less than in the base case, GDP per capita is greater than in the base case, and vice versa. This arises because GDP grows partly as population grows (more people produce more goods) and partly with increasing capital and total factor productivity (loosely, technological advance) (see Kirby 2021). The latter two are not dependent on population and hence if population growth slows, GDP growth

Fig. 2 Population from 1960 to 2001 simulated by the integrated model (dashed line) and as projected by the UN Population Division (2019a), solid line

Fig. 4 Demand for groundwater simulated in the base case (solid line in each plot) and the scenarios. The scenarios are as follows: **a** (top left plot) climate change, CC-HD – hot-dry, CC-HW—hot-wet, CC-WD—warm-dry, CC-WW—warm-wet; **b** (top middle plot) EFlow_Incr/Decr—environmental flow increase or decrease (the latter also being a desalination scenario—see Sect. 2.2), Sed_Decr— reduced sedimentation, Dam_Incr—increased storage; **c** (top right plot) Lo/Hi_Yield_Incr—low or high rate of yield increase, Reduced_ Cotton—reduced cotton; **d** (bottom left plot) Popn_Incr/Decr— population increase or decrease, GDP_Incr/Decr—GDP increase or decrease; **e** (bottom right plot) Wealth_Eq/Uneq—more equal or more unequal wealth distribution.

will not slow as much, so GDP per capita will rise (and vice versa). In the base case, the GDP per capita in index terms of 6910 is about 18 times the GDP per capita simulated in 2020; together with the current GDP per capita in Pakistan of about $1200, this implies a GDP per capita in 2100 of about $22,000 (at constant prices). The population in 2100 of 341 m (low population scenario) or 463 million (high population scenario) are well within the upper and lower 80% probabilistic bounds (of 282 and 571 m) of UN (2019a) using the probabilistic method (UN 2019b).

The scenarios which deal only with physical changes to water supply and demand (climate change, dam storage, sedimentation and environmental flows scenarios) all have the same population and GDP per capita as the base case. In the model, a purely physical change to water supply or demand has no impact on population or GDP. The population, GDP and wealth inequality scenarios all affect the population and GDP per capita, because of the linked behaviour of population and GDP. The scenarios with higher or lower yield growth, and reducing cotton, all have a small impact on population and GDP per capita. This arises from lesser or greater crop yields requiring more or less land to produce the food demands, and hence a greater or lesser agricultural workforce. A lesser agricultural workforce requirement results in more people migrating from rural to urban centres, and taking up non-agricultural employment (and vice versa). This latter form of employment has a higher rate of GDP growth than agriculture, which in turn reduces (slightly) the population growth.

Groundwater demand in the combined scenarios

Figure 5 shows the groundwater demand in all scenarios, with the dry and wet extreme climate change combination scenarios grouped in the two plots in the figure. With the exception of the dry extreme climate change scenario (CC-HD), the best-fit polynomial lines for the scenarios all fall below the base case line. Note that the delta flow reduction scenario (labelled 4 in the two plots in Fig. 5) is also the desalination scenario (as explained in Sect. 2.2). It should be noted that, as shown in Fig. 4, the impact of many of the scenarios (such as population, GDP, yield increases or decreases and reduced cotton) is of similar magnitude. In Fig. 5, the first scenario added (reduced yields) has the greatest absolute impact, and there is less demand to be reduced by the scenarios added subsequently. The last added scenario (population/GDP) therefore has a smaller absolute effect, but it has a similar proportionate effect on groundwater demand (as expected from Fig. 4). To show the impact of different orders of adding scenarios, we examined the consequence of each being the first added to the CC-HD scenario. The reduction in demand from that of the CC-HD scenario at 2100 was 34% (increasing yields), 31% (reduced cotton), 9% (increased storage), 7% (delta flow reduction/desalination), 8% (sedimentation control) and 23% (population/GDP). The percentage reductions from the CC-WW scenario were 38, 31, 18, 9, 16 and 27.

Table 3 Simulated population and GDP per capita in 2100 in the scenarios and the combined scenarios

Scenario	Base	Lo_Yield Incr	Hi_Yield Incr	Reduced Cotton	GDP Decr	GDP Incr	Popn Decr	Popn Incr	Wealth Eq	Wealth Uneq	Combined scenarios	
											2 to 5	6
Population in 2100, million	404	405	404	404	459	368	341	463	387	424	403	350
GDP per capita in 2100[1]	6910	6851	7002	6979	2653	16,967	7519	6460	7033	6746	7061	11,600

Note that the scenarios of changes to climate, dam storage, sedimentation and environmental flows all have the same population and GDP per capita as the base case. Combined scenario 1 has the same population and GDP as the Hi-Yield increase scenario.

[a]GDP per capita is based on an index (with GDP in 1960 = 100) divided by the population in millions.

## Population and GDP per capita in 2100 in the combined scenarios

The simulated population and GDP per capita results in 2100 for the combined scenarios are shown in Table 3. Except for combined scenario 6, the results are the same as, or very similar to, those of similar individual scenarios. In combined scenario 6, the population is similar to that of the individual (uncombined) reduced population growth scenario, or the individual increased GDP scenario, while the GDP per capita of the combined scenario is about midway between that of the individual scenarios.

Discussion

In the base case, many features of the simulation (including population, GDP, wealth distribution, food production, crop yield, areas of crops, demand for irrigation water, surface water availability and river flows at several points in the basin) compare reasonably well to the historical values for the period 1960–2020 (as shown by Kirby 2021).

The climate change scenario results are not dissimilar to those of the sophisticated treatment by Ahmad et al. (2021), who examined four scenarios somewhat analogous to the four used here, for the period 2046–2075. Their results, while expressed differently (in terms of a change in the water balance at canal command and provincial level in the Indus Basin irrigation areas of Pakistan), can be used to derive the implied change in groundwater demand. Their four scenarios imply the changed groundwater demands shown in Table 3, which also shows the results from the four scenarios used here. The change in groundwater demand in the hot-dry and warm-wet scenarios is similar to that in the scenarios of Ahmad et al. (2021), with the other two scenarios showing only a modest change from the base case. The results in this paper are shifted to somewhat greater demand than those of Ahmad et al. which could be due to the increased food demand with the increase in population, which was not considered by Ahmad et al. Table 4 also shows that the changed rate of sedimentation scenario in the results reported here has an impact on groundwater demand in 2050 similar to that implied by the change in sedimentation storage in 2050 modelled by Ahmad et al. (2021).

The modelled crop yields in 2100, as noted in the scenarios section, are below current potential yields (AARI 2020) even in the high yield increase case, and are therefore eminently achievable. The assumption of increased crop yields per unit area, together with constant crop coefficients in the model that determine the water demand, produce an implied increase in crop yields per unit of water. Furthermore, since we varied the rate of yield increases per unit area in the high yield increase and low yield
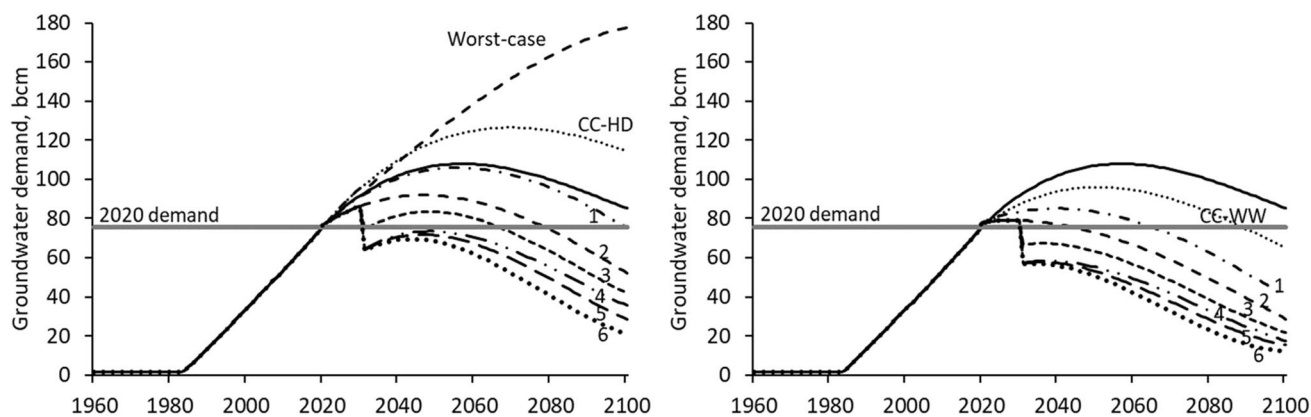
Fig. 5 Demand for groundwater simulated in the base case (solid line in each plot) and the scenarios. The scenarios are as follows: left. dry extreme climate change, CC-HD together with the added effects of 1. increased crop yields, 2. reduced areas of high water use crops (exemplified by cotton), 3. increased water storage, 4. decreasing delta flow/desalination water supply, 5. sedimentation control in the water stor-ages, 6. reduced population growth/increased GDP growth; right. wet extreme climate change, CC-WW together with the same added effects. The final combined scenario is that labelled "Worst-case" in the left-hand chart. The thick grey line shows the simulated ground-water demand in 2020

Table 4 Change in groundwater demand in 2060 from the base case for four projected climate change scenarios, and in 2050 from the base case to a changed dam sedimentation scenario: this paper compared to Ahmad et al. (2021)

Scenario, this paper	Scenario, Ahmad et al. (2021)	Implied change in GW demand, this paper	Implied change in GW demand, Ahmad et al. (2021)
Hot-dry	Low flow—dry	17.2	15.6
Hot-wet	High flow—dry	− 1.6	2.4
Warm-dry	Low flow—wet	4.3	− 1.6
Warm-wet	High flow—wet	− 13.2	− 17.0
Dam Sedimentation	Dam sedimentation	− 2.2	− 1.1

increase cases, the implied increase in crop yields per unit of water also varies: crop yields per unit of water increase about 20% faster in the high yield increase case than in the base case, whereas in the low yield increase case they increase about 10% slower than in the base case. Pakistan yields per area and per unit of evapotranspiration are lower than in many other parts of the world, and less than half that in the best performing areas (Zwart and Bastiaans-sen 2007), including nearby Punjab and Haryana in India (Sharma et al. 2010). Sharma et al. (2010) noted that in the Indo-Gangetic Basin, the yield per unit area and per unit of evapotranspiration were generally correlated; the implied assumption of increases in yields per unit of water being the same as that of yields per unit of water in the model used here is consistent with that observation. Furthermore, Gaydon et al. (2021) showed that in rice–wheat systems in the Pakistan Punjab, the best choice of crop variety (amongst three current varieties), number of irrigations, timing of sowing and nitrogen application rate resulted in yields per unit area that could be increased by up to 57% (wheat) or 38% (rice) with a significant decrease in evap-otranspiration compared to current farmer practice. The

yields per unit of evapotranspiration could thus increase significantly more than the yields per unit area in both wheat and rice (Table 5 of Gaydon et al. 2021). Thus, the assumptions of yields per unit area and the implied assumption of yields per unit of water consumed as evapotranspiration are both plausible.

Our general finding that water security can be achieved is consistent with Davies and Young (2021) and Young et al. (2019). However, there are many differences of detail in the different modelling approaches and in the scenarios. Davies and Young (2021) used a constant rate of annual population growth of 1.3% and a constant rate of GDP growth in their base case of 2.26%, whereas population growth in our base case falls from about 2% in 2020 to zero in 2093 (and slightly negative in 2100). Annual GDP growth in our model starts at about 4% in 2020, similar to the rate for the last two decades (e.g. PBS 2021, which gives figures in domestic currency, and World Bank 2020, which gives figures in US$), falling in the future (consistent with PWC 2017) to about 3% in 2100 with the decreasing growth in labour input as a result of slowing population growth. The Davies and Young (2021) assumption leads to a population from 2040

to 2050 about 20 million lower than our base case projection and that of the UN median projection (UN 2019a), which implies lower food and hence irrigation water demand. Our high GDP growth scenario assumes a gradual increase in the growth rate, finishing at 6% per annum by 2100, 2% above the base rate. Davies and Young (2021) examined a scenario in which GDP is 1.73% above the base case, similar to our assumption, but in their case the increase is constant with time. They did not examine the major impact on water demand of changes to population growth. However, consistent with our findings, Young et al. (2019, in the Executive Summary) noted that "The largest increases in demand will be for irrigation. Population and economic growth are the main drivers, but climate warming will contribute significantly". Our general findings overall agree with those of Davies and Young (2021) and show that water security is achievable in Pakistan.

In addition to the impact of population and GDP growth, we examined inequality in wealth. Our scenarios appear implausible—but they teach us something. Pakistan's wealth distribution has remained roughly equal, with a Gini coefficient of between about 0.28 and 0.33, since 1985 (World Bank 2020). The two scenarios end up with Gini coefficients of 0.18 (more equal distribution of wealth) and 0.45 (less equal) in 2100, which are well outside any historical experience. However, we can see from Fig. 3 that even these extreme changes to the wealth distribution had less impact on the demand for groundwater than did most other scenarios. The implication is that, whatever the merits of policies for alternative wealth distributions, they would appear to be marginal for water security.

The simulations show that with increasing population and GDP growth, food demand and hence water demand in the base case will increase in Pakistan to about 2055. This results from the population growth rate being greater than the rate of increase in crop yields, with the additional effects of changing diets and somewhat declining water availability at certain times due to dam sedimentation. After that, assuming that crop yields continue to increase, the falling population growth rate results in food demand and water demand decreasing in the base case to 2100. In terms of groundwater demand, this translates to a reduction of about 22% from the 2050s to 2100, but the demand in 2100 remains about 13% greater than the current demand. It may also be noted that different crops have different rates of yield increase which, together with the dietary preference changes, leads to a different overall mix of crops for which water must be supplied. For example, sugarcane, which has lower yield growth than most of the other crops represented, takes a larger share of land and hence water by 2100.

Several factors could significantly reduce or increase the demand for groundwater in the peak demand period of the 2050s, and some that increase demand could also shift the peak to later in the century. The factors include climate change, environmental flow reserves/desalination supplies, the volume of water storage, increases in crop yields, population growth and GDP growth. Yu et al. (2013) also concluded that increases in water storage and crop yields are key strategies for Pakistan. Whereas we have, for convenience, treated environmental flows as a potential supply, they might better be considered as another demand for water. In most cases except for environmental flow reserves, desalination and the volume of water storage, the impact of these effects continues to grow to 2100. We have used one simulation for the case of an environmental flow scenario or a desalination scenario, with a changed flow from 2030. However, the need for environmental flows is immediate, whereas flows from desalination are likely to be well into the future. Sediment management in the water storages and wealth distribution each has a small effect by the 2050s, but a larger effect by 2100. A key point is that to reduce groundwater demand, early implementation of strategies is desirable; in this context, Faruqui (2004) suggested that annual population growth should be reduced to 1.5% by 2015, yet in 2020 it is about 2% (though falling). However, no factor considered here will alone reduce demand in the peak period to less than the current use. Demand in 2100 is less than current use in only four of the scenarios considered here: the warm-wet climate change scenario, reduced population growth, the higher rate of increase of crop yields and the reduction of cotton cropping.

However, combining the changes in two or more scenarios substantially reduces the peak groundwater demand in mid-century, even in the case of an extreme dry climate change scenario. The combined scenarios also result in demand late in the century below the current demand (and falling), substantially so if all six changes were implemented in full. Groundwater used to meet these levels of demand may well be seen as sustainable. In a wet future climate, even three or four of the changes might be seen as sustainable, and the trade-off between sustainable groundwater use and environmental flows to the delta potentially may be avoided. However, in a drier future climate, sustainable groundwater can be achieved but only at the cost of trade-offs with other sustainability goals, such as environmental flows to the delta.

Strategies to implement the changes in crop mix (which we have implemented using cotton as a proxy for a range of changes that could be made) could be implemented by policies on prices and market distortions (Anjum and Zia 2020), including water pricing and water trade. Some policies would also affect imports and exports. However, an implicit assumption in the results is that the imports and exports of crops (foods) remain similar, relative to production, as it is currently. Detailed analysis of such issues is beyond the scope of the simple model outlined here.

In a desalination scenario, the obvious source of water is brackish groundwater. The volume of groundwater in the Indus Basin is very large, but much of it is unused because it is saline. With this as a source, groundwater use for irrigated agriculture may not be as unsustainable as it currently appears. Better quality irrigation water may also improve crop yields. However, the economics of desalination must change before this becomes a large-scale feasible option. The energy requirements of desalination also lead to a trade-off amongst sustainability goals.

One factor not considered in the scenarios is that of climate change impacts on yields. Kirby et al. (2017) noted literature projections of yield declines with increasing temperatures, and used a scenario in which future yield increases were less than otherwise expected. In the present analysis, that is equivalent to the scenario with a lower rate of yield growth. However, if a crop were to become unviable in parts of Pakistan, another crop would likely be substituted. The general effect would be analogous to the decreasing cotton scenario—except that water demand could increase or decrease, depending on which crop became unviable and which alternative was to be grown. Another factor we have not considered is that of variation in water demand resulting from different spatial patterns of future crop distributions. If, for example, the increase in crop areas in the future was concentrated in higher rainfall areas, the additional water required from irrigation would be less than if the future crops were grown in the more arid southerly regions of Punjab and Sindh. A third factor we have not considered is the role of prices or market distortions (e.g. Ejaz and Ahmad 2017). These have a bearing on the crop mix, production and import/export in Pakistan, and policies to change market incentives appropriately would help achieve sustainable water use—though, as we have shown, other factors must also be considered.

Finally, the worst-case scenario sounds a note of caution. A hot-dry future climate, combined with higher population/lower GDP growth and a lower yield growth (which could be linked to the hotter conditions if they impair yields), leads to a greatly increased demand for groundwater by 2021. It is the only scenario combination which shows no sign of levelling off and decreasing before the end of the century. There could in principle be even worse scenarios, such as if rice production were greatly increased in search of export earnings. These worst-case scenarios would not only be unsustainable but they would offer no prospect of returning to a sustainable future for the foreseeable future, and would likely damage aquifers permanently through the ingress of saline water. Given these adverse consequences, monitoring progress on population growth rates, changes to crop yields and the mix of crops planted, as well as climate change trends, would

enable detection of problems and hence accelerated implementation of policy and management options.

Our results demonstrate the scope for achieving sustainable water use (particularly groundwater use) in Pakistan, and also the prospect of difficult sustainability trade-offs. As noted by Moeller et al. (2014), a model-based approach, such as the one presented here, can inform evaluation processes and frame meaningful discussions with decisions makers, from which actions might emerge.

Conclusions

We conclude that, consistent with the findings of many studies in the literature, the water outlook for Pakistan is likely to worsen in coming decades, and more groundwater is likely to be used for irrigation. However, in the second half of the century, the combined effects of slowing population growth and increases in crop yields could see the situation reverse, with decreasing demands for groundwater for domestic food production.

Several factors could increase or decrease the demand for and use of groundwater, including socio-economic policies (changes to population growth rates, GDP growth rates and wealth inequality), agricultural and water management (crop yield increase, reducing areas of high water using crops, new dam storage, storage sedimentation control, desalination water supply, changing flow to the delta), and climate change. These factors encompass both supply and demand for water. Although desirable on other grounds, sedimentation control and dealing with wealth inequality appear to be the least influential in terms of the impact on future groundwater demand.

Water security and sustainable water use appear to be achievable for Pakistan by combining several strategies to reduce water demand. In wetter possible future climates, it may be possible to achieve sustainable use without many difficult trade-offs amongst sustainable development goals. However, if the future climate is much drier, sustainable groundwater use though achievable will involve trade-offs with other sustainability goals, such as environmental flows to the delta.

Declarations

Conflict of interest None.

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