Futures 133 (2021) 102831

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

From narratives to numbers: Spatial downscaling and quantification of future water, food & energy security requirements in the Indus basin

Wouter J. Smolenaars [a,*], Arthur F. Lutz [b], Hester Biemans [a,c], Sanita Dhaubanjar [b,d], Walter W. Immerzeel [b], Fulco Ludwig [a]

[a] *Water Systems and Global Change Group, Wageningen University, Wageningen, The Netherlands*
[b] *Department of Physical Geography, Utrecht University, Utrecht, The Netherlands*
[c] *Wageningen Environmental Research, Wageningen, The Netherlands*
[d] *International Centre for Integrated Mountain Development, Kathmandu, Nepal*

ARTICLE INFO

Keywords:
Sustainable Development Goals
Indus basin
Water-food-energy nexus
Spatial population projections
Downscaling
Scenario building

ABSTRACT

Integrated adaptation strategies are needed to achieve the highly interlinked Sustainable Development Goals (SDGs) for water, food- and energy security in the Indus basin. However, detailed quantitative scenarios for the plausible dimensions of future resource security requirements under socio-economic development are lacking. Here we define three quantitative and spatially downscaled scenarios for future water, food and energy requirements in the Indus basin and we assess the implications of socio-economic development for the integrated resource security challenge. High-resolution gridded scenarios for resource security requirements are developed by combining three regionalised and spatialised Shared Socioeconomic Pathways (SSPs) with quantitative regional water, food and energy security thresholds. The results demonstrate that by 2080 basin level water- and energy security requirements are likely to at least double and potentially triple compared to the current situation. Food requirements could increase only marginally and double at most. Migration and urbanisation additionally drive the growing requirements to spatially converge around the largest cities of the basin. This demonstrates that socio-economic development increases the complexity of the water-food-energy security challenge by increasing its magnitude and spatial concentration. Future research and policymaking should anticipate for this heterogeneous growth of resource security challenges when developing adaptation strategies.

1. Introduction

The transboundary Indus basin is one of the most vulnerable areas in the world (De Souza et al., 2015; Immerzeel et al., 2020). The basin is shared by Pakistan, India, Afghanistan and China, causing considerable hydro-political tensions (Laghari, Vanham, & Rauch, 2012). The densely populated lowlands of the Indus basin are arid and largely depend on melt water coming from the upstream mountainous areas for its societal and economic functioning (Biemans et al., 2019; Wijngaard et al., 2018). The bulk of water resources

* Corresponding author.
E-mail address: wouter.smolenaars@wur.nl (W.J. Smolenaars).

https://doi.org/10.1016/j.futures.2021.102831
Received 13 July 2020; Received in revised form 1 July 2021; Accepted 25 August 2021
Available online 28 August 2021

is allocated to sustain one of the largest irrigation system in the world (Wijngaard et al., 2018), while water is also required for hydropower, on which the regional energy production depends considerably (Molden, Vaidya, Shrestha, Rasul, & Shrestha, 2014). The multi-sectoral water demand has pushed the system beyond its biophysical limits. The Indus basin is among the most water stressed in the world, relying significantly on the unsustainable over-extraction of groundwater (Cheema, Immerzeel, & Bastiaanssen, 2014; Richey et al., 2015; Wanders, Wada, & Van Lanen, 2015), while water, food and energy security requirements in the basin are currently not being met (Molden et al., 2014; Rasul, 2014; Yang, Ringler, Brown, & Mondal, 2016).

Climate change also alters the water supply of the basin and affects the viability of food- and energy production (Dahri et al., 2021; Lutz, Immerzeel, Kraaijenbrink, Shrestha, & Bierkens, 2016; Lutz et al., 2019). Moreover, the Indus basin is projected to face rapid socio-economic development (UN, 2015). The growth in population and economic development will exponentially increase societal demand for water, food and energy resources (Rasul, 2016; Vinca et al., 2020; Wijngaard et al., 2018). Satisfying these demands will put additional stress on the already limited water resources (Yang et al., 2016). The combination of a precarious present-day situation with rapidly diverging gap between water resource supply and demand, makes achieving and maintaining the water security *Sustainable Development Goal* (SDG 6) in the Indus basin extremely challenging. Given their water-dependency, the food and energy security SDGs (2 & 7, respectively) are also at risk (Rasul, 2014, 2016). Integrated adaptation efforts that simultaneously ensure water, food and energy security are therefore essential (Immerzeel et al., 2020; Rasul, 2014).

To develop adaptation strategies that fit the complex water-food-energy security challenge of the Indus basin, it is critical to have a quantitative understanding of the magnitude and range of the future adaptation deficit (Chang, Li, Yao, Zhang, & Yu, 2016). However, the SDGs are defined at the global scale in a universal, qualitative manner. Its indicators, and their interaction with socio-economic development, need to be quantified respective of the regional context to become actionable security targets (Weitz, Nilsson, & Davis, 2014; Yillia, 2016). Given the dominant role of socio-economic changes in the vulnerability of the Indus basin (Immerzeel et al., 2020; Momblanch et al., 2019; Wijngaard et al., 2018), this requires a clear operationalisation of water, food and energy security thresholds, and insight into how associated resource requirements within the basin may develop over time under socio-economic development (Weitz et al., 2014; Yillia, 2016). Such information must be available at disaggregated sub-national levels to be of direct use in adaptation policy making (Rasul, 2014; Weitz et al., 2014).

Considerable advances have been made in understanding the hydrological and climatological processes of South-Asian river basin. Regional water-food-energy nexus modelling studies (Momblanch et al., 2019; Vinca et al., 2020; Wada et al., 2019; Wijngaard et al., 2018) have however predominantly relied on exerts from global studies to represent the future socio-economic context and assess its interaction with the hydrological system(Biemans & Siderius, 2019). Despite several qualitative assessment of regional nexus security challenges (Rasul, 2014, 2016), quantifications of future water, food, and energy security requirements in the Indus basin remain largely derived from global studies(Bauer et al., 2017; Falkenmark, Rockström, & Karlberg, 2009; Gain, Giupponi, & Wada, 2016).

However, these quantifications have been established at coarse country, basin or even macro-region scales using universal water, food and energy security thresholds. The socio-economic development context in these studies is sourced from the basic global narratives of the global *Shared Socio-economic Pathways* (SSP) framework(Riahi et al., 2017). Key socio-economic variables that drive the resource security challenge in the Indus basin, such as population growth and urbanisation patterns (Rasul, 2016), follow global assumptions and ignore the Indus basin's heterogenous policy- and socio-economic context. Another complication is that the projected resource requirements are often spatially allocated to current population distributions. Regional future urbanisation- and migration trends are not accounted for in global projections, while these are key drivers that affect both the magnitude and spatial distribution of domestic water, food and energy security requirements in the Indus basin (Chang et al., 2016; Rasul, 2016; Roy et al., 2019; Siddiqui et al., 2019). Spatially explicit socio-economic scenarios that are tailored to the context of the Indus basin are therefore needed to understand future nexus security challenges, as a benchmark for assessing the SDGs and to formulate and evaluate adaptation policies.

In the absence of spatially detailed scenarios, existing assessments do not capture the dynamic resource security context of the

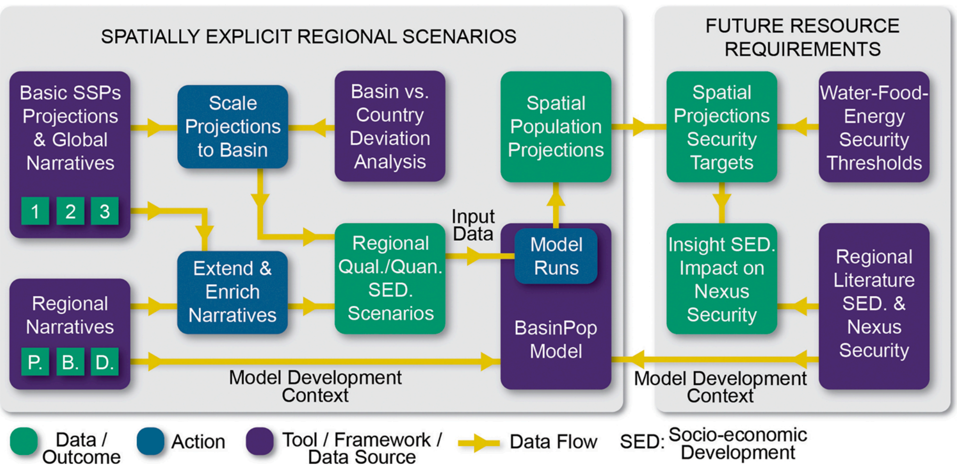

Fig. 1. Overview of methodological approaches, interlinkages between research steps, and outcomes.

Indus basin. They provide little understanding of the heterogeneity of future water, food and energy security requirements at the critical local level, where socio-economic upstream-downstream conflicts and trade-offs in resource allocation can arise. The objective of this study is to provide quantitative, downscaled and spatially explicit regional scenarios that constrain the potential ranges of future water, food and energy security requirements in the Indus basin. We hereby define security requirements as the resources required directly to meet domestic resource security thresholds. Furthermore, we aim to assess the implications of socio-economic development for the integrated water-food-energy security challenge of the basin from a nexus perspective.

Our approach (see Fig. 1) combines scenario building with a top-down modelling approach. First, we develop regionalised socio-economic scenarios by extending three basic global SSPs with specific regional development narratives. The scenarios are then spatialised by BasinPop, a population distribution model that was designed specifically to simulate regional urbanisation- and migration processes. Gridded scenarios of future population distributions in the Indus basin are combined with regionally defined per-capita water, food, and energy security thresholds to create spatially explicit scenarios of future security requirements in the Indus basin. Finally, we reflect on the implications of our findings from a water-food-energy nexus perspective and discuss the role these findings play as a benchmark for developing local Indus basin Development Goals.

2. Materials and methods

2.1. Population distribution model (BasinPop model)

Several studies have spatialised global population projections using the SSP framework (Jones & O'Neill, 2016; Murakami & Yamagata, 2019; van Huijstee, van Bemmel, Bouwman, & van Rijn, 2018). However, the models used to develop these projections have been designed for the global scale. These projections thereby inherently contain simplifications and assumptions on population and urbanisations patterns that may not necessarily hold true for the complex and unique socio-political context of the Indus basin. To spatialise our regional scenarios we have therefore developed *BasinPop*, a population distribution model that was designed to simulate the unique regional context of migration and urbanisation in the Indus basin.

The BasinPop model builds upon the methodological approach used in the global population distribution models HYDE (Klein Goldewijk, Beusen, Van Drecht, & De Vos, 2011) and 2UP (van Huijstee et al., 2018). Expansion of urban area and distribution of population both occur based on suitability mapping using weighted layers of explanatory variables, within the constraints of boundary conditions. BasinPop adds five normalized spatial layers of explanatory variables *(distance to urban area*, *distance to major city*, *distance to road network*, *highland-to-lowland* and *terrain suitability*) and three spatial layers of boundary conditions (*border zone*, *current urban area* and *terrain suitability*) to create a suitability map. The distribution procedure additionally uses four socio-economic indicators as input data (*total population, urbanisation fraction, maximum urban density* and *mean urban density)*.

The spatial layers that form the basis for the suitability mapping have been selected to mirror historical migration and urbanisation patterns in the region and to account for projected future patterns. This is most evident in the explicit differentiation between the *distance to general urban areas* and the *distance to major cities* as separate explanatory variables. Urbanisation in the wider South-Asia region has historically concentrated at far higher rates towards dense megacities than elsewhere in the world (Cox, 2012; Ellis & Roberts, 2015; Mustafa & Sawas, 2013). The major city variable hence opens the possibility, if a scenario calls for this, of shifting the gravity of urban expansion towards the areas surrounding major population centres. Additionally, the wider Hindu-Kush Himalaya region faces a strong migratory pattern from the highlands to the economically stronger lowlands (Siddiqui et al., 2019; Tiwari & Joshi, 2015). The *highland-to-lowland* layer was developed based on the altitude of sub-regional administrative units to account for this trend in the suitability map. Lastly, the complex geopolitical situation of the Indus basin has considerably affected the development and urbanisation of areas in the vicinity of international borders (Bala & Krishan, 1982; Kannan, 2015). To reflect this the *border zones* boundary condition was added which reduces the suitability of areas close to international borders.

The other explanatory variables, *terrain suitability* and *distance to road network*, are generic explanatory variables also used in other models (Klein Goldewijk et al., 2011; van Huijstee et al., 2018). The *terrain suitability* layer also figures as a boundary condition, providing the biophysical limits to population expansion. Lastly, *current urban area* has been added as a boundary condition to spatially define the current urban extent and dynamically consider the geographical location of pre-existing urban areas in future timesteps. Detailed information on the characteristics and development of the explanatory variables and boundary conditions can be found in Annex 3.

The BasinPop model runs on a 5 arcmin resolution and simulates spatial population density development between two timesteps of any given length on a per-country and -scenario basis using the following algorithm for every simulation run:

- First, for each country basin level external population- and urbanisation development numbers are read to determine the change in total urban- and rural population in the timestep. The future population totals are combined with projected changes in mean urban population density to assess the required change in urban area.
- Next, a gridded suitability map is created by aggregating the explanatory variable layers with a scenario-specific weighting to indicate the suitability of each cell to become urbanized. The suitability of areas that fall within the border zone are corrected by the factor belonging to the relevant scenario.
- If the urban area is projected to grow, the required additional urban area is allocated iteratively by converting rural grid cell with the highest suitability until the total required urban area is met. The allocation of new urban area takes the available space for urban expansion into consideration by using the suitable terrain factor.

- Finally, the change in urban and rural population is distributed separately over the urban- and rural areas. The change in population of each grid cell is based on the suitability map. If the total urban or rural population is projected to grow, the most suitable grid cells obtain the largest population increases. A shrinking population leads to the highest population reduction in the least suitable cells. The urban population allocation procedure first allocates over the newly urbanized areas before allocating over the entire urban area. The terrain suitability factor and a scenario-specific maximum population density factor are used to ensure that population totals within cells do not exceed allowable limits.
- For the next timestep, the *current urban area* layer is updated with the newly urbanized areas and the explanatory variable layers are updated. The final population density map forms the new starting point for the next iteration.

We have developed the BasinPop model to be flexible and dynamic so it may be used to project a wide range of plausible futures. In contrast to the relatively static suitability maps in the 2UP and HYDE models, our suitability mapping procedure dynamically recalculates the values of the explanatory variable layers for every simulation based on the relevant socio-economic context and the outcomes of the previous timesteps. Similarly, weightings of explanatory variables and the values of boundary conditions can be easily adapted and may vary for each scenario. This allows us to adhere to distinct urbanisation trends outlined in regionalized socio-economic scenarios. We furthermore allocate population dynamically for both urban and rural areas, using the suitability map to simulate which rural areas are more likely to face population change.

2.1.1. Calibration

Gridded historical timeseries of population distributions for the Indus basin are scarce and existing global datasets, such as HYDE (Klein Goldewijk et al., 2011), have generally based historical population distributions for the region on a static contemporary suitability map. Therefore, we calibrated the BasinPop model with census data at district level for Pakistan over the period 1998–2017, and India for the period 2001−2011. Census data was spatialised using sub-national shapefiles of the Global Administrative Areas dataset (Hijmans, 2015). For Afghanistan, no census data could be obtained, and the Chinese share of the basin was determined to be too scarcely populated for calibration purposes.

We corrected the gridded population distributions of the HYDE dataset for 2000 to respective populations at districts level in 1998 and 2001 for both countries. Gridded population layers were used as the basis for separate model runs for both countries over the respective census periods. We used census data for 2017 and 2011, and urban density data estimations of Cox (2015) as socio-economic input data. Simulated gridded population projections were then aggregated using the district shapefiles and compared to census data. The best combination of explanatory variable weightings was identified to approximate the observed population development per district in both countries using non-linear least squares regression. The weighting was assumed to be consistent across all four riparian states.

2.2. Developing spatially explicit regional socio-economic scenarios

Previous integrated modelling studies for the Indus basin and global assessments of future water-food-energy requirements based their scenario context on the *Shared Socio-economic Pathways* (SSP) framework (O'Neill et al., 2014). To maintain consistency with previous studies and benefit from pre-existing datasets, the core of our regional socio-economic scenarios builds onto the SSP framework. The framework offers several '*basic SSPs*' that consist of qualitative global socio-economic development narratives and quantitative projections of main socio-economic indicators (O'Neill et al., 2017). A key step in applying the SSP framework in regional impact assessments is to extend the basic SSPs towards more elaborate scenarios that fit the research objectives and regional context (Absar & Preston, 2015; O'Neill et al., 2017).

We used a three-step approach that integrates quantitative, qualitative and spatial elements to extend the basic SSPs towards spatially explicit regional scenarios required by the scope of our research (see Fig. 1 and sections 2.2.1 to 2.2.3). To encompass large bandwidth in plausible socio-economic futures the contrasting SSP1 (optimistic, low challenges) and SSP3 (pessimistic, high challenges) narratives were selected as the starting points for the regional scenario development (O'Neill et al., 2017). Additionally, the 'middle of the road' narrative SSP2 was selected, as this moderate scenario may be more suitable for policy making.

2.2.1. Qualitative extension & enrichment of basic SSPs

Qualitative future storylines were developed for the wider Hindu Kush Himalaya (HKH) region during several workshops with a heterogenous group of stakeholders (Roy et al., 2019; Siddiqui et al., 2019; Wester, Mishra, Mukherji, & Shrestha, 2018). Each HKH narratives qualitatively illustrates a unique and plausible socio-economic future for the region considering the interwoven context of social, political, economic, climatic and environmental drivers. The storylines were developed towards 2080 with 2030 and 2050 as important intermediate steps. The multi-disciplinary stakeholder group developed two contrasting futures (*Downhill*; pessimistic and *Prosperous*; optimistic) and a moderate (*Business as usual*) storyline.

To integrate the HKH narratives with the basic SSPs we used a matching technique, in which we qualitatively assessed similarities between the regional narratives and global SSP narratives. Matching based on 12 indicators (see Annex 1, for a more elaborate explanation of narrative matching see Kok, Pedde, Gramberger, Harrison, and Holman (2019) demonstrates that the Prosperous, Business as Usual and Downhill narratives fit well with respectively SSP1, SSP2 and SSP3. The integration created three extended narratives towards 2080; '*SSP1-Proserous*', '*SSP2-Business as Usual*' and '*SSP3-Downhill'* (abbreviated as *SSP1-P*, *SSP2-B* and *SSP3-D* henceforth*)*. This led to the addition of specific migration- and urbanisation storyline elements to the scenarios, and the elaboration of inter-regional cooperation- and governance indicators. The extended narratives provide the qualitative context of the regional scenarios.

2.2.2. Quantitative scaling of basic SSPs

Quantitative country level economic(Dellink, Chateau, Lanzi, & Magné, 2017) and demographic (Samir & Lutz, 2017) projections have been developed for each of the SSP narratives. However, none of the countries in the Indus basin fall completely within its boundaries. A study by Reimann, Merkens, and Vafeidis (2018) used observed growth differences within countries to tailor national SSP projections to smaller regions. Similarly, we used a spatially explicit historical data analysis to scale the basic SSP projections for population and GDP per capita to the Indus basin context. For both indicators we have determined ‘basin factors’ that represent the historical discrepancy between socio-economic indicators at the national level and for the basin-share of each country and applied these to the basic national SSP projections. It was assumed that these basin factors remain static. The scaled projections form the quantitative core of the regional scenarios

$$P_b(n,c,s) = P_b(n=2015,\ c) + P_b(n=2015,\ c)*\left(\prod_{n=2015}^{n} G_{ps}(n,c,s) - 1\right)*F_{bp}(c) \tag{1}$$

$$E_b(n,c,s) = E_{nat}(n=2015,c) * \left(\prod_{n=2015}^{n} G_{es}(n,c,s)\right) * F_{be}(c) \tag{2}$$

The scaled population projections were achieved using Eq. 1 where P_b is the population for the basin-share of country ‘c’ at year ‘n’ for scenario ‘s’, G_{ps} is the SSP national annual population growth rate for country ‘c’ at year ‘n’ for scenario ‘s’, and F_{bp} is the basin population factor for country ‘c’. F_{bp} was determined by assessing the difference in growth rate between the basin-share of each country and the national average over the period 1990–2015 on the basis of the gridded HYDE 3.2 dataset (Klein Goldewijk et al., 2011). Comparison of the HYDE basin factor with a similar assessment using provincial census statistics for India over the same period yield similar results (see Annex 2). We used the HYDE 3.2 dataset to determine the initial 2015 F_{bp} for the basin-share of every country.

Similarly, the scaled GDP projections were obtained using Eq. 2, where E_b is the average GDP per capita in the basin-share of country ‘c’ at year ‘n’ for scenario ‘s’, E_{nat} is the national GDP per capita (PPP) at year ‘n’ for country ‘c’; G_{es} is the SSP national annual GDP per capita (PPP) growth rate for country ‘c’ at year ‘n’ for scenario ‘s’; and F_{be} is the basin GDP factor for country ‘c’. F_{be} was determined by analysing the present-day difference in GDP per capita between the basin-share of each country and the national average. We used the sub-national GDP per capita layer of the DRYAD dataset (Kummu, Taka, & Guillaume, 2018) and the gridded total population layer of the HYDE 3.2 dataset for 2015 to obtain the population weighted difference between GDP per capita in the basin-share of each country and national averages.

To improve the representation of urbanisation and population dynamics, available national level urbanisation projections were reviewed (Jiang & O’Neill, 2017). Due to differences in definitions and general lack of consensus on urbanisation patterns in the region, these could not be regionalised further. However, the HKH narratives stipulate that, although the manner and form of urbanisation may differ, the urban population share in the region will increase steeply in any of the plausible futures (Roy et al., 2019), while the SSP projections maintain a low urbanisation trend for developing countries in the economically pessimistic SSP3 variant (O’Neill et al., 2017). Regional projections comparatively suggest that a continuation of the rapid urbanisation trend in the decades to come appears inevitable (Ellis & Roberts, 2015; Siddiqui et al., 2019). Therefore, the low-end SSP3 urbanisation projection was replaced with the mid-range projection of SSP2 in the SSP3-D scenario. For SSP1-P and SSP2-B scenarios the respective basic SSP quantifications were maintained.

2.2.3. Spatialising the regional scenarios

The BasinPop model was used to spatially downscale the regional scenarios. For all three scenarios, the change in population distributions from 2015 towards 2080 was simulated over seven timesteps. The 2015 population density map of the HYDE 3.2 dataset (Klein Goldewijk et al., 2011) was used as the base population map. The socio-economic input data for the starting point and every subsequent timestep were sourced from the quantitative elements of the regionalised scenarios. Other variables and parameters were assessed separately for each scenario by interpreting the regionalised narratives:

- Urban density values were established by adjusting 2015 national urban densities from Cox (2015) with a scenario-specific annual change factor. For Afghanistan no data was available, and the population-weighted basin average urban density was taken. Global patterns of urban densification demonstrate the density of urban areas to first rise steeply and then slowly decreases as the standard of living increases (Klein Goldewijk, Beusen, & Janssen, 2010; Malpezzi, 2013). Urban density in South-Asia is still among the world’s highest, but has been decreasing by about 1% per year, as urban growth has geared towards low density sprawl in peripheral areas around major cities (Angel, Parent, Civco, & Blei, 2011; Ellis & Roberts, 2015). Angel et al. (2011) projects the realistic range of annual urban density decline between 0% and 2% towards 2050. The regional scenarios similarly project high-density urbanisation to persist in the foreseeable future in the SSP3-D scenario, while the SSP1-P scenario describes a shift towards planned urban expansion. Therefore, it is assumed that urban density will remain static in the SSP3-D scenario. In the SSP1-P pathway the decrease in urban density is assumed to continue at the 1% annual pace and then accelerate to 2% annually as the standard of living rises. For SSP2-B urban density change was assumed to be a continuation of the current 1% annual decline.
- The maximum allowable population density was assessed using the 2015 extremes of the HYDE dataset. The current maximum within the study area was found within the urban confines of Lahore at around 30.000 people/km^2, while the highest global value is

48.000 people/km^2 in Karachi. It was therefore assumed that in the SSP1-P scenario, the increase of the urban density ceiling is minimal and limited to 32.000 people/km^2. In the SSP3-D scenario it was assumed to reach the high-end 48.000 people/km^2 mark. Lastly, in the SSP2-B scenario the maximum density was assumed to be in the middle of the extreme scenarios at 40.000 people/km^2. This ceiling was scaled at the cell-level by the suitable terrain fraction to obtain the allowable maximum.
- No quantitative estimations could be found on population dynamics near of international borders. Therefore, the suitability of grid cells within the border zone is reduced by 25 % in SSP2-B scenario and 50 % in the SSP3-D scenario, representing decline in transboundary cooperation. In the ‘SSP1-Pros’ scenario the effect was omitted.

The scenario-specific weighting of the explanatory variables used for the runs were first established on the results of the calibration procedure over the historical period. These initial weightings were assumed to be valid across all basin countries and stay constant through time. In the SSP2-B scenario, the importance of each variable was assumed to remain consistent with the historical patterns found and thus the weightings of the calibration procedure were maintained. For the SSP1-P and SSP3-D scenario, several adjustments were made to the basin-level weightings by interpreting the regionalised narratives:

- The growth of mega cities in South Asia is associated with a lack of economic opportunities in the peripheral areas and the political capital and governance required to steer urbanisation in a more spread out fashion (Jabeen, Farwa, & Jadoon, 2017; Kraas, 2007).

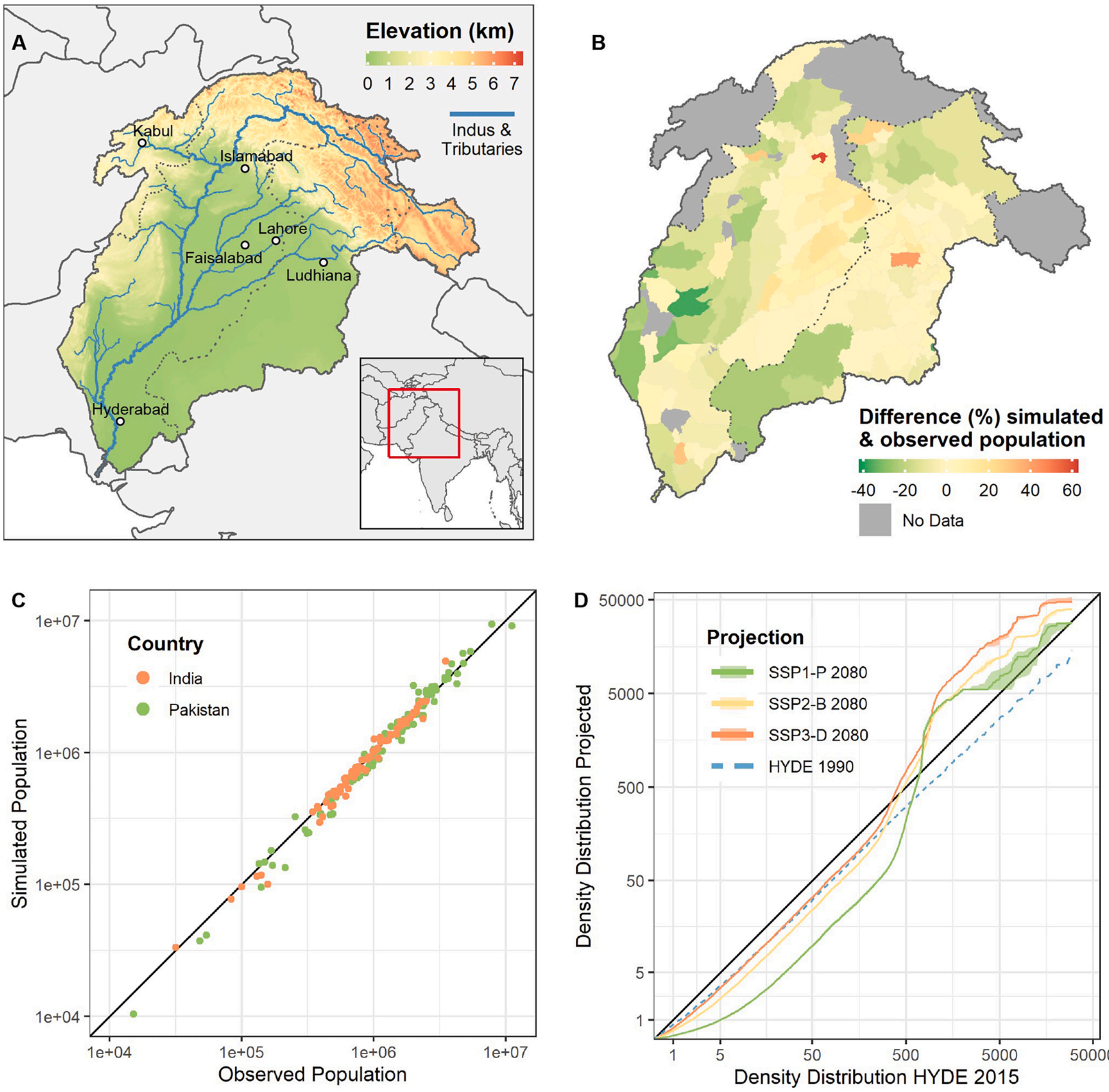

Fig. 2. map of the study area showing the Indus basin outline, main hydrological network and elevation (A) spatial projection of the difference between simulated population using the BasinPop model and observed census population at district level (B), comparison of simulated versus the observed population at district level (C), the sorted population density of all populated grid cells in the Indus basin for the three scenarios in 2080 and the uncertainty range (shaded) in comparison to the HYDE 2015 baseline (D). The HYDE 1990 distribution is added for reference.

This is suggested to lead to large shares of dense informal settlements and increasing tendency of migration towards major economic centres. Stronger governance, however, may see urbanisation to be spread out over primary and secondary urban areas alike (Ellis & Roberts, 2015). Therefore, in the SSP3-D scenario the influence of the 'distance to major city' layer was assumed to be 50 % higher compared to the SSP2-B scenario, while the influence of the 'distance to urban area' layer was assumed to be 50 % lower. In the SSP1-P scenario, the weighting of the 'distance to major city' layer was assumed to be reduced by 50 %.
- Highland to lowland migration has historically occurred as a resilience strategy in times of economic downturn (Siddiqui et al., 2019; Tiwari & Joshi, 2015). Hence, this factor was assumed to have an increasing influence in the economically pessimistic SSP3-D pathway, while it is of lesser importance in the SSP1-P pathway. In the SSP3-D scenario it's weighting was therefore increased by 100 % compared to the SSP2-B scenario. In the SSP1-P scenario it was reduced by 100 %, negating the effect completely.

To assess the influence of these assumptions an uncertainty analysis was conducted for every scenario, consisting of model runs in which the assumed values were individually and collectively scaled by 10 % and 20 % in both directions (see Fig. 2D).

2.3. Defining resource security thresholds

To determine the influence of socio-economic development on future basin-scale water- food and energy security requirements we use existing national per-capita thresholds for each of the riparian countries. In case no quantitative national thresholds were available, thresholds for the nearest riparian state were used.

2.3.1. Water security

Here, we limit the water security definition to only consider sufficient availability to perform essential day-to-day domestic activities, rather than economically driven water demand. Water security thresholds are defined at the national level in Pakistan and India. Both countries distinguish water security in rural and urban areas. Pakistan has set urban water security at 120 L per capita per day and rural water security at 45 L per capita per day(Parry, 2016). The rural-urban discrepancy of India's water security definitions is slightly bigger. Here, urban water security is defined at 130 and rural at 40 L per capita per day(Aayog, 2018). For Afghanistan and China, no national definition could be established. Therefore, the Pakistani guidelines were used.

2.3.2. Food security

We limited the food security definition to only the quantitative availability of sufficient calories. The Indian national dietary guideline distinguishes between the minimum food availability norm for rural and urban areas, based on the more active lifestyles dominant in rural areas. Rural inhabitants are required to have at least 2400 daily kcal available to them, while the urban norm is defined considerably lower at 2100 daily kcal (NIN, 2011). In China the national dietary guideline similarly defines 2320 kcal and 2250 kcal as the threshold for respectively rural- and urban daily caloric availability (Fengying, Jieying, & Xuebiao, 2010; Liangshu, 2002). Pakistan does not make a distinction based on lifestyle, but uses a bare minimum caloric requirement of 1910 kcal per capita per day and a preferable benchmark of 2350 kcal per capita per day for the general population (Ishaq, Khalid, & Ahmad, 2018). For this study, the higher-end threshold was used. The Afghani food security threshold is considerably lower, aiming for at least 2100 kcal per day for every individual(IRA-ME, 2012).

2.3.3. Energy security

Quantitative definitions for energy security at country level are sparse. Rao, Min, and Mastrucci (2019) estimates present energy requirements in India for 'decent living standards' at 5 Gigajoules per capita per year (1400 kW h/cap/year) and suggest these may grow to approximately 10 Gigajoules by 2050. These estimates represent broader economy-wide energy requirements and therefore also include energy needs for transportation, education and economic welfare. We instead limit energy security to domestic electricityrequirements, although other energy sources are widely used for domestic purposes in the Indus basin, in particular for cooking. We assume an electricity security threshold of 600 kW h per capita per year for the urban population and 260 kW h per capita per year in the entire Indus basin, based on a study for India (Narula, Reddy, Pachauri, & Dev, 2017).

2.3.4. Spatial projections

Lastly, the per capita definitions of resource security were combined with the gridded rural and urban population projections to create spatial insight into the change in resource security requirements (see Fig. 1). The gridded changes in resources requirements were aggregated at district level for Pakistan and India, and the county level of China. To maintain comparability within the basin, in Afghanistan future changes were aggregated at provincial level because of the small geographical area of these administrative units.

3. Results

3.1. BasinPop model calibration & performance

The calibration procedure at district level found the *distance to urban area* layer to be the most important variable with a weighting at 95. The second most influential variable was found to be *distance to major city* layer at 15, indicating that the district containing major cities have additional pull over regular urban areas. The *terrain suitability* and *distance to main road* layers were both found to have minor influence on population change, at 5 and 2 respectively. The *highland-to-lowland* layer was weighted at 1, thus not influencing the spatial patterns of population change over the historical period.

A comparison of our calibrated model performance to historical census data (see Fig. 2B, C) demonstrates that the simulated district level population totals match the observed census data well with a Pearson correlation coefficient of 0.97 and an R^2 of 0.94. The model performance is shown to be best for the high- to moderate-density, predominantly urban districts (Fig. 1C). Simulated population totals in the highest population districts show a minor overestimation, while the population in districts with lower density are marginally underestimated, especially in Pakistan. A spatial analysis of model performance similarly demonstrates a positive bias towards the densely populated Indus plains and a negative bias in mountain and desert areas. Part of this may well be explained by discrepancies in natural population growth rates, since these are higher in the peripheral areas, but are not considered in the model.

Compared to the 2015 baseline, the projected population distributions in all three scenarios skew towards the high-density grid cells, simulating a gradual urban-rural transition (Fig. 2D). However, the steepness and form of this transition varies between the scenarios, which shows that the model is capable of simulating various types of urbanisation and migration patterns. The uncertainty analysis (Fig. 2D) showed that these urban-rural patterns remain consistent under the changes in model parameters and weightings, and that the uncertainty related to the assumed parameters only has a minor influence on the population distribution of high density grid cells.

Table 1
Qualitative socio-economic context and key quantitative figures for three regional scenarios.

Ind.	Adm.	Scenario									
			SSP1-Prosperous			SSP2-Business as Usual			SSP3-Downhill		
		2015	2030	2050	2080	2030	2050	2080	2030	2050	2080
Population (millions)	AF	12	16	20	23	17	25	34	19	30	49
	CH	0.028	0.028	0.026	0.022	0.028	0.027	0.023	0.028	0.027	0.023
	IN	84	98	105	92	103	119	120	108	137	171
	PK	169	202	225	218	212	258	288	225	303	412
	Basin.	**266**	**315**	**351**	**334**	**332**	**402**	**442**	**352**	**470**	**631**
GDP per capita (PPP, billions 2005 USD $)	AF	1 327	2 262	7 409	30 282	1 940	4 118	14 345	1 782	2 846	5 875
	CH	5 337	14 765	29 299	41 919	12 751	21 151	34 437	11 662	15 417	18 076
	IN	5 077	12 054	31 494	71 125	10 569	21 020	45 338	9 315	12 687	16 478
	PK	2 565	4 473	12 305	35 011	3 998	8 392	23 530	3 534	5 020	8 251
	Basin.	**3 310**	**6 712**	**17 781**	**44 692**	**5 922**	**11 869**	**28 758**	**5 216**	**7 120**	**10 296**
Urbanisation (% of total population living in urban areas)	AF	25	41	58	75	33	43	57	33	43	57
	CH	59	68	81	90	61	70	78	61	70	78
	IN	34	49	67	84	42	53	67	42	53	67
	PK	37	55	70	85	47	58	69	47	58	69
	Basin.	**37**	**52**	**68**	**84**	**45**	**55**	**68**	**45**	**55**	**68**
Urban Density (cap. per km^2)	AF	13 888	11 944	8 838	4 861	11 944	9 794	7 247	10 242	10 242	10 242
	CH	6 100	5 246	3 882	2 135	5 246	4 302	3 183	6 100	6 100	6 100
	IN	12 200	10 492	7 764	4 270	10 492	8 603	6 367	12 200	12 200	12 200
	PK	15 800	13 588	10 055	5 530	13 588	11 142	8 245	15 800	15 800	15 800
	Basin.	**13 888**	**11 944**	**8 838**	**4 861**	**11 944**	**9 794**	**7 247**	**10 242**	**10 242**	**10 242**
Urbanisation patterns	Basin.	–	Decentralized, planned and sprawling			Tendency towards major cities, later sprawling			Strong tendency towards dense megacities		
Migration patterns	Basin.	–	Planned, favourable			Concentration to urban areas			Increasing highland to lowland		
Regional Cooperation	Basin.	–	Constructive cooperation			Sectoral cooperation, but inadequate			Low cooperation, lack of trust, resource conflict		
Global cooperation	Basin.	–	Strong bonds, free trade			Key alliances for resource sharing			More regionalised		
Climate change scenario	Basin.	–	RCP4.5			RCP6.0			RCP8.5		
Innovation	Basin.	–	High			Moderate			Low		
Resource Use Intensity	Basin.	–	Sustainable			Unstable			High and unsustainable		
Water security threshold (L/d/cap.)	AF	120 urban areas / 45 rural areas.									
	CH	120 urban areas / 45 rural areas.									
	IN	135 urban areas / 40 rural areas.									
	PK	120 urban areas / 45 rural areas.									
Food security definition (kcal/d/cap.)	AF	2100 urban & rural areas.									
	CH	2320 urban areas / 2250 rural areas.									
	IN	2100 urban areas / 2400 rural areas.									
	PK	2350 urban & rural areas.									
Energy security definition (kWh/y/cap.)	AF	600 urban areas / 230 rural areas.									
	CH	600 urban areas / 230 rural areas.									
	IN	600 urban areas / 230 rural areas.									
	PK	600 urban areas / 230 rural areas.									

3.2. Indus basin socio-economic scenarios

The regionalisation of the SSPs and the application of the BasinPop model resulted in three spatially explicit regional scenarios (see Table 1 and Fig. 3).

3.2.1. SSP1 - prosperous

The SSP1-P scenario envisions a region with sustainable economic and social development based on strong international cooperation. Global climate change is contained to a moderate RCP4.5 scenario. Hydro-political tensions in this scenario are considerably lessened, owing to closer trade ties and mutually beneficial economic cooperation between the riparian states. Economic progression is strong, with GDP per capita in the basin increasing as much as thirteen-fold in 2080, driven by rapid technological innovation. Population growth is projected to be comparatively low, peaking at an increase of 40 % around the middle of the century, and dropping to 33 % by 2080 compared to the 2015 baseline. Urban expansion is comparatively spread out over major cities and secondary cities

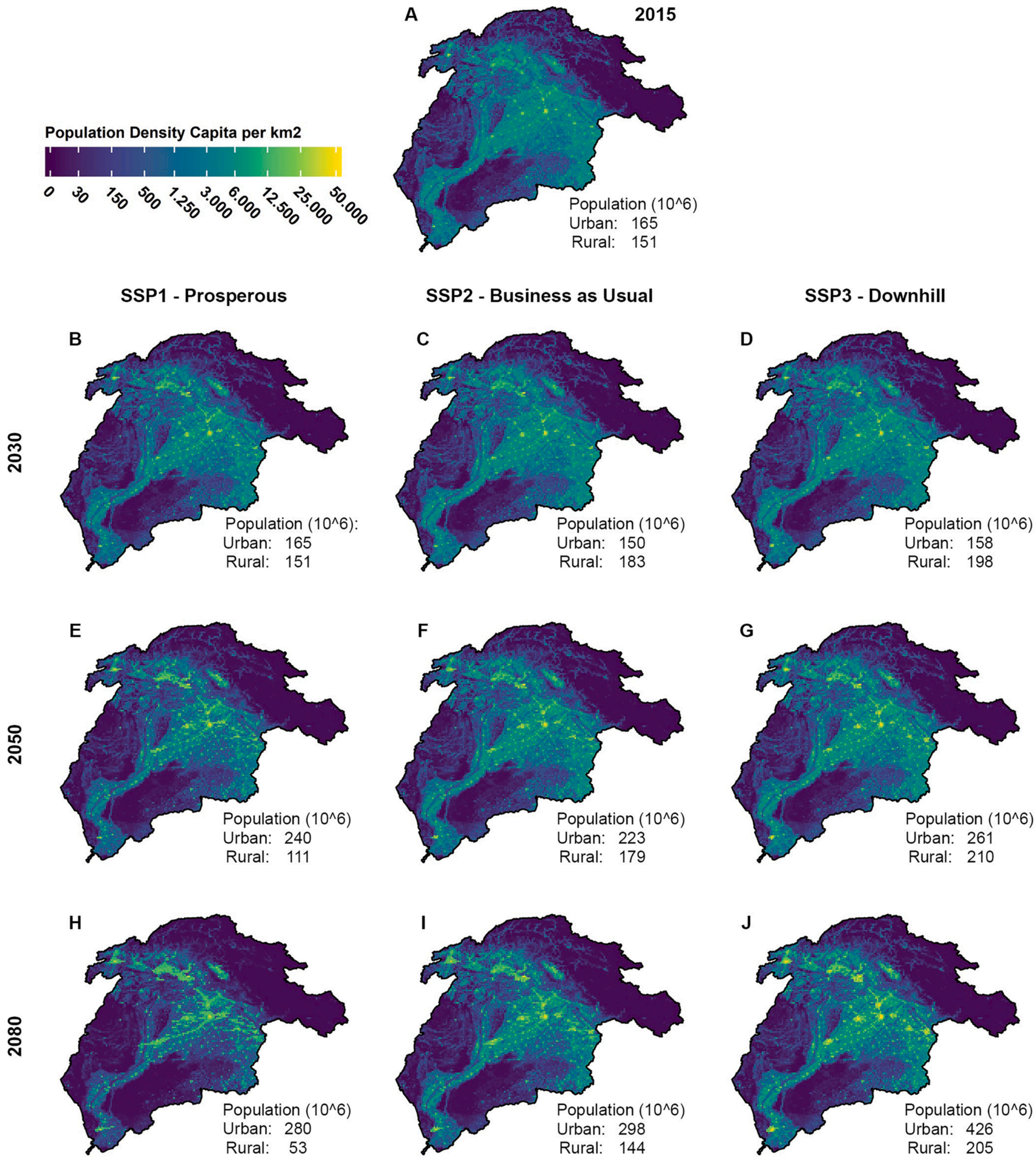

Fig. 3. Simulated future population density in the Indus basin in 2030, 2050, and 2080 for three regional scenarios.

alike. The majority of Indus basin population is concentrated in sprawling, moderate density patches in the foothills of the high Asian mountain ranges, and on the Indus plains along the river's tributaries (see Fig. 3B, E, H). However, the combination of stagnating population growth and continuing urbanisation have a compounding effect on rural depopulation. This leads to a sharp division in population density between rural and urban areas towards 2080, despite the comparatively low urban density.

3.2.2. SSP2 - business as usual

The SSP2-B scenario describes a future in which current processes and patterns are largely sustained. Economic growth maintains its rapid pace and the GDP per capita grows more than eight-fold. Although the pace of population growth steadily decreases, the total number of inhabitants in the basin by 2080 still increases by over 60 % compared to the baseline. This increases the pressure on the available resources and inhibits widespread sustainable resource use practices. This scenario faces a moderate to high climate change outlook, corresponding to an RCP6.0 scenario. Despite relatively strong national governments, the historical urbanisation bias towards the basins largest cities continues to dominate this scenario. However, over the course of the scenario, increasing prosperity and the strengthening of governance capacities cause a shift away from concentration in major urban areas towards planned and more spacious urban expansion by 2080. As can be seen in Fig. 3C, F and I, this initially leads to the expansion of the basin's major cities, followed by more moderate density expansion around these cities, along the highway network and current secondary urban areas.

3.2.3. SSP3 - downhill

The SSP3-D scenario imagines a plausible future with meagre economic development and non-abiding tensions between the riparian states. Similar political strife at the global level leads to the inability to control emissions, leading to a strong RCP8.5 climate change scenario. The economic output of the region still progresses, but under pressure from a steep 145 % increase in population by 2080, the GDP per capita only increase marginally. Consequently, the standard of living and economic security of the Indus basin inhabitants throughout this scenario remains low. Due to a lack of institutional strength, national governments are unable to steer the patterns of migration and urbanisation trend towards the economically most affluent regions, resulting in a strong concentration towards megacities. The continued rapid population growth and comparatively high population density leads to development of several densely populated clusters around the present-day major cities (see Fig. 3D, G, J). However, population growth is so high that even with the strong urbanisation signal, rural depopulation remains limited. In fact, Afghani rural population density is projected to continue increasing.

3.3. Future water, food, and energy security requirements

The combination of the regional socio-economic scenarios with regional resource security thresholds demonstrates that at basin level, water, food and energy requirements will increase in all three scenarios and for all three resources (see Fig. 4). The requirements for water security demonstrate the steepest growth, increasing by at least 90 % in SSP1-P by 2080, but possibly by as much as 220 % in SSP3-D, compared to contemporary requirements. This growth is most pronounced in Afghanistan, where drinking water requirements in 2080 in the SSP3-D scenario increase by 390 % compared to the 2015 baseline. The energy requirements show a similar increase of between 80 % and 200 %. The total caloric requirement to achieve food security on the other hand shows only a relatively small increase of 20 % in the SSP1-P scenario. However, under pressure from population growth it will more than double in the SSP3-D scenario. The higher growth rate of water- and energy security requirements as compared to food security is explained by the former being driven by both population growth and urbanisation. For food security on the other hand, the caloric requirements are slightly higher for rural inhabitants. Urbanisation hence somewhat moderates the effect the population growth on the size of the total food security challenge.

The spatially explicit assessment of future security requirements demonstrates that urbanisation, migration and population growth have a compounding effect on the geographical disparity of water-food-energy requirements (see Fig. 5). In all three scenarios, resource requirements increasingly converge towards several hot spot regions. The foothills of the Himalayas and the lowlands along the Indus river see the strongest growth in requirements, with district surrounding, or containing, major cities demonstrating exponential increases. Similarly, the areas around Kabul, Afghanistan are projected to require up to six-fold more water and energy resources than they do in the 2015 baseline to meet security requirements. On the other hand, the district located in highland- and desert

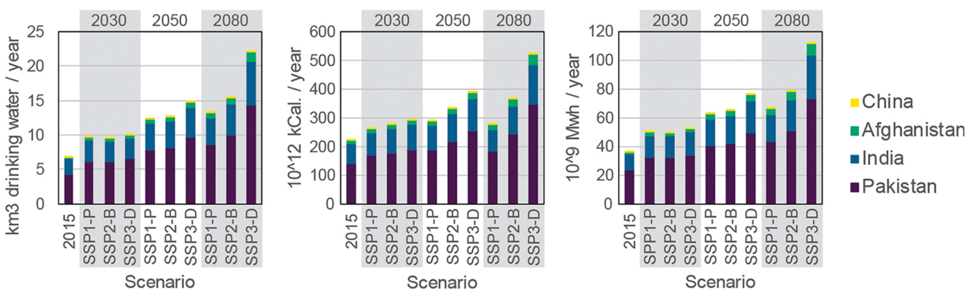

Fig. 4. total water, food, and energy security requirements at the basin level for three regional scenarios.

areas face a reduction in the magnitude of resource security requirements.

4. Discussion

4.1. Limitations, uncertainties & opportunities

During the development of the BasinPop model, the emphasis was on accurately representing urban expansion because this is the major driver of future water, food, energy security challenges (Rasul, 2016). Consequently, the model utilises the same suitability map to spatialise rural and urban population changes. Relevant factors for rural out-migration, however, do not necessarily align with the regionalised factors of urban expansion that form the basis of the suitability maps. For example, the increasing frequency and intensity of heatwaves and drought events due to climate change could affect rural outmigration (Tiwari & Joshi, 2015). However, it is still very uncertain if and how climate change will affect future migration patterns. In addition, besides future population dynamics other socio-economic variables, such as changing economic potential and value chain dependencies for key resources, are also of relevance for the spatial manifestation of adaptation challenges. Further model development could therefore focus on separating the suitability map of rural population change from the suitability map for urban expansion, consider future climatic conditions and expand to

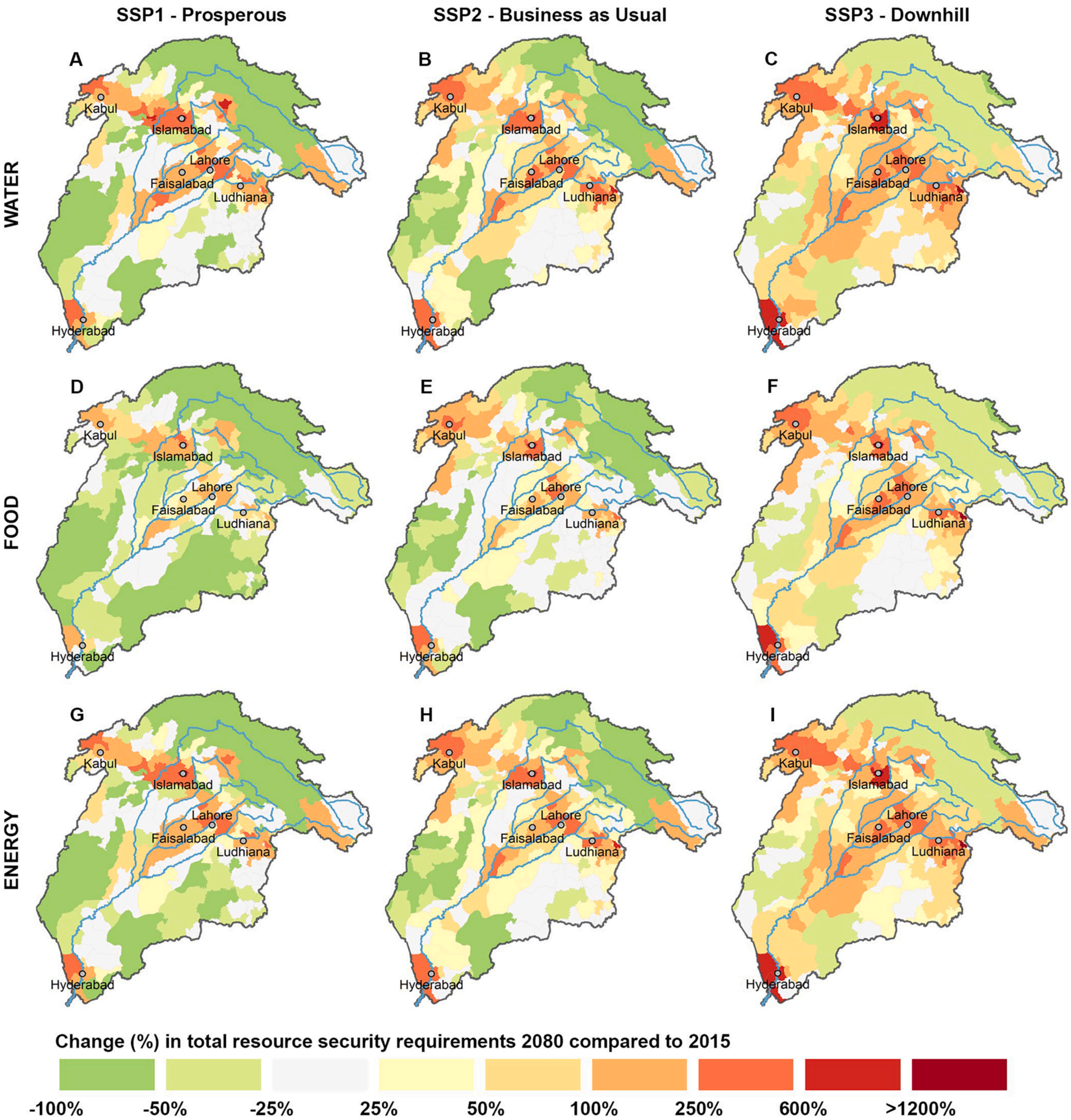

Fig. 5. change in magnitude of water- (A, B, C), food- (D, E, F) and energy (G, H, I) resources required to attain direct domestic security thresholds in 2080 as compared to 2015.

include more economic metrics that aid the development of location specific adaptation measures.

The weighting of BasinPop explanatory variables in this study was based on historical patterns, trends outlined in qualitative regional literature and by interpreting the scenario narratives. A rigorous stakeholder engagement approach could be an alternative manner to set the weights. The BasinPop model is highly flexible, has a rapid run-time and visualises results near instantaneous. This makes it suitable to be used for co-creation purposes and to facilitate stakeholders discussions (Biemans & Siderius, 2019) and opens the opportunity to also apply the model as a tool during workshops with regional actors and policymakers. Such an approach may yield additional plausible population maps and build local support in research outcomes. Furthermore, the flexible design of the model does not restrict its usage to the Indus basin. Its architecture can be applied for similar assessment in other river basins.

The indicators used to represent water- food- and energy security thresholds were simplified and only reflect the direct quantitative aspect of domestic resource security. However, sufficient resource availability does not mean that wider security goals are met or that resources are distributed equally. For instance, diets must also be sufficiently diverse and nutritious to achieve food security (FAO, 2019). For water resources upstream usage practices may affect downstream water resource availability and quality. Also, due to economic development average per capita demand for water, food and energy resources may grow to considerably surpass the policy-defined security thresholds. For example, per capita domestic water consumption in most developed countries exceeds the highest per capita security requirements of this study, and the riparian states of the Indus basin are projected to follow a similar trend (Bijl, Bogaart, Kram, de Vries, & van Vuuren, 2016). Similarly, the per capita energy consumption in OECD countries at 8000 kW h per capita is more than ten-fold higher than the highest per capita energy-security threshold used in this study (IEA, 2019). The economically driven growth in resource demand may conflict with the universal availability of resources to meet the security requirements. To account for such equity issues, the actual required growth in the domestic availability of water, food and especially energy resources could be considerably higher than the requirements presented in our study, especially in the SSP1-P scenario.

4.2. Implications of socio-economic development for the integrated water-food-energy security challenge

Despite the outlined limitations, our scenarios consistently demonstrate resource requirements to increase and spatially concentrate. This indicates that there are several implications of future socio-economic development for the integrated water-food-energy security challenge in the Indus basin.

Foremost, our results show that the water resources required for domestic water security could potentially triple from 7 km^3 to 22 km^3 in the Indus basin. Compared to the projected change in water availability and demand at basin scale, this still accounts for a relatively small fraction of the total future water budget of approximately 250 km^3 annually (Laghari et al., 2012; Wijngaard et al., 2018). However, due to urbanisation, migration and population growth the increasing requirements will concentrate around the basin's largest cities, with local tenfold increases. Currently, access to safe drinking water in the region is low and a large share of the Indus basin inhabitants source their water locally from groundwater (Mukherji, Scott, Molden, & Maharjan, 2018; Rasul, 2016). The groundwater dependency has already led to a substantial drop in urban groundwater tables in Lahore and Islamabad (Basharat, Sultan, & Malik, 2015). The concentrated exponential surges in domestic water requirements projected in this study could exacerbate local overexploitation of water resources and increase inequity in water access. From a water security perspective, the challenges may therefore not lie with allocating an increasing share of the basin's water resources to growing domestic requirements, but with adapting to the increasing spatial disparity between water supply and demand. The development of improved infrastructure that guarantees universal access to water resources in hotspot areas therefore appears crucial not only from a qualitative water security perspective, but also to ensure sufficient availability.

Our results indicate that food security requirements may rise considerably, potentially doubling under the SSP3-D scenario by 2080. Irrigated agriculture is already the main water user in the Indus basin (Wijngaard et al., 2018) and possibilities for further agricultural land-use expansion in the basin are limited. Additional food production must therefore largely come from intensification of existing agriculture, including the conversion of rainfed to irrigated agriculture. This is likely to require additional blue water resources (Rasul, 2014). However, our scenarios show that considerable urban expansion will occur in the fertile Indus river valleys, encroaching into areas that host the largest share the basin's irrigation system (Wijngaard et al., 2018). To achieve food security it is likely that agricultural water demand will increase in areas where drinking water requirements are also increasing. Urban-agricultural water competition in the basin is already high and an exacerbation of this phenomenon may threaten both water- and food security in the Indus basin (Flörke, Schneider, & McDonald, 2018). Our analysis confirms claims by Rasul (2016) that regionally, more food needs to be produced on less land with scarcer water resources.

Finally, satisfying rising energy requirements may also place constrains on water resources. The basin faces energy deficits and has a large untapped hydropower potential (Gernaat, Bogaart, van Vuuren, Biemans, & Niessink, 2017). Infrastructure to harvest more of this potential is being developed rapidly (Molden et al., 2014). A promising adaptation avenue may be found in the construction of multi-purpose hydropower dams to increase the control over the allocation of water through space and time. This could potentially benefit water- and food security but could have broad scale negative impacts on other sustainability goals such as biodiversity, fisheries and sediment transport. However, projected spatial patterns of population distribution demonstrate that water and energy requirements are increasingly peaking on the Indus plains, while most hydropower potential and production is found in the remote highland areas (Molden et al., 2014). Although hydropower does not directly consume the water, it may aggravate intersectoral water competition and increase pressure on upstream-downstream linkages.

The water-food-energy nexus perspective hence demonstrates that socio-economic development intensifies the complexity of the integrated resource security challenge in two ways; firstly, by increasing the magnitude of future resource security requirements, and secondly by geographically converging the area in which the growing challenge manifests itself. In addition to the temporal convergence of pressure on water-food-energy security due to climate change (Lutz et al., 2016), socio-economic development may therefore drive the increasing pressure to also concentrate spatially, rising greatly in several hotspot areas, while staying the same, or even reducing, in other parts of the basin. Further integrated modelling studies and policymaking in the Indus basin must consider the progressive spatiotemporal discrepancy in future resource security challenges when designing adaptation strategies towards achieving the water-food-energy SDGs.

4.3. From global SDGs to local Indus Development Goals

To better assess what is needed to achieve development goals in the Indus there is a need to define adaptation goals from a more regional perspective. This can be done by translating global Sustainable Development Goals to specific and quantified Indus Basin Development Goals (IDGs). The security requirements presented in this study can provide a quantitative benchmark to monitor the realization of these IDGs. To further define the IDGs, subsequent research could focus on quantifying the second-order nexus resource requirements and adaptation targets (i.e. water-for-food and water-for-energy) under climate change within the basin, with the help of integrated modelling tools that can account for trade-offs and synergies between them.

5. Conclusion

Socio-economic development is an important driver of water, food, and energy resource requirements in the Indus basin. Our results show that under socio-economic development, the urban population of the Indus basin is likely to grow considerably and converge towards the basin's largest cities located in the foothills of the high Asian mountain ranges and the Indus plains. Water- and energy security requirements were found to be driven by both population growth and urbanisation, and by 2080 are projected to increase by factor 2.3 (1.9–3.2) and 2.2 (1.8–3.1) respectively compared to the 2015 baseline. The growth of the food requirements over the same period is limited to a factor 1.6 (1.2–2.4), as it is driven only by population growth. However, under the projected changes in population distribution, the weight of resource requirements within the basin was shown to progressively concentrate geographically as well. This drives the magnitude of security requirements in several hotspot areas around the major cities to grow exponentially, while requirements in highland- and desert areas decrease.

The scenario analysis illustrates that socio-economic development has a compounding effect on the complexity of the integrated water-food-energy security challenge of the Indus basin, as it both increases the magnitude of challenges and concentrates them. In this light, adaptation strategies that can moderate the rapidly increasing spatial disparities in interlinked water-food-energy pressure appear essential on the road to achieving the SDGs. The scenarios provide critical input for the robust development of such strategies to be conducted in follow up studies and policymaking.

Lastly, the BasinPOP model developed in this study has proven to be a useful and adaptable tool to quantify regional population dynamics. Because of its flexibility it may furthermore be suitable to use in with workshops stakeholders and policy makers. The model architecture may be of use to conduct similar spatially explicit assessment in other complex river basins.

Acknowledgements

We would like to extend our gratitude dr. Azeem Ali, dr. Hameed Jamali, Arjuna Srinidhi and Samaa Mufti for providing critical insight into the socio-economic context of the Indus basin and reflecting on the implications of our results. Work of all the authors is supported by the SustaIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.futures.2021.102831.

References

Aayog, N. (2018). *Composite water management index: A tool for water management*.

Absar, S. M., & Preston, B. L. (2015). Extending the shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environmental Change Part A, 33*, 83–96.

Angel, S., Parent, J., Civco, D. L., & Blei, A. M. (2011). *Making room for a planet of cities*.

Bala, R., & Krishan, G. (1982). Urbanization in a border region: A case study of India's border districts adjoining Pakistan. *The Geographical Journal*, 43–49.

Basharat, M., Sultan, S., & Malik, A. (2015). *Groundwater management in Indus Plain and integrated water resources management approach.* Lahore, Pakistan: Pakistan Water & Power Development Authority (WAPDA).

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., … Mouratiadou, I. (2017). Shared socio-economic pathways of the energy sector–quantifying the narratives. *Global Environmental Change Part A, 42*, 316–330.

Biemans, H., & Siderius, C. (2019). Advances in global hydrology–crop modelling to support the UN's Sustainable Development Goals in South Asia. *Current Opinion in Environmental Sustainability, 40*, 108–116.

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassen, T., & Immerzeel, W. W. (2019). *How important is snow and glacier meltwater from High Mountain Asia for downstream agriculture?*.
Bijl, D. L., Bogaart, P. W., Kram, T., de Vries, B. J., & van Vuuren, D. P. (2016). Long-term water demand for electricity, industry and households. *Environmental Science & Policy, 55*, 75–86.
Chang, Y., Li, G., Yao, Y., Zhang, L., & Yu, C. (2016). Quantifying the water-energy-food nexus: Current status and trends. *Energies, 9*(2), 65.
Cheema, M., Immerzeel, W., & Bastiaanssen, W. (2014). Spatial quantification of groundwater abstraction in the irrigated Indus basin. *Groundwater, 52*(1), 25–36.
Cox, T. (2012). World urban areas population and density: A 2012 update. *The New Geography*.
Cox, W. (2015). Demographia world urban areas. *11th Annual Edition*.
Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, S., Ahmad, B., Ahmad, S., … Kabat, P. (2021). Climate change and hydrological regime of the high-altitude Indus basin under extreme climate scenarios. *The Science of the Total Environment, 768*, Article 144467.
De Souza, K., Kituyi, E., Harvey, B., Leone, M., Murali, K. S., & Ford, J. D. (2015). *Vulnerability to climate change in three hot spots in Africa and Asia: Key issues for policy-relevant adaptation and resilience-building research*. Springer.
Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the shared Socioeconomic Pathways. *Global Environmental Change Part A, 42*, 200–214.
Ellis, P., & Roberts, M. (2015). *Leveraging urbanization in South Asia: Managing spatial transformation for prosperity and livability*. The World Bank.
Falkenmark, M., Rockström, J., & Karlberg, L. (2009). Present and future water requirements for feeding humanity. *Food Security, 1*(1), 59–69.
FAO. (2019). *The state of food security and nutrition in the world 2019: Safeguarding against economic slowdowns and downturns*.
Fengying, N., Jieying, B., & Xuebiao, Z. (2010). Study on China's food security status. *Agriculture and Agricultural Science Procedia, 1*, 301–310.
Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability, 1*(1), 51–58.
Gain, A. K., Giupponi, C., & Wada, Y. (2016). Measuring global water security towards sustainable development goals. *Environmental Research Letters, 11*(12), Article 124015.
Gernaat, D. E., Bogaart, P. W., van Vuuren, D. P., Biemans, H., & Niessink, R. (2017). High-resolution assessment of global technical and economic hydropower potential. *Nature Energy, 2*(10), 821–828.
Hijmans, R. (2015). *GADM database of global administrative areas, version 3.6*. Retrieved from: https://gadm.org/data.html.
IEA, I. (2019). *World energy statistics and balances, IEA*. Paris (France): OECD.
IMB. (2019). *Cities: A service providing city points from IMB's CPPI database*. Retrieved from https://www.arcgis.com/home/item.html?id=f3cbd682dc404e699bf40a0bd2d25936.
Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature, 577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y.
IRA-ME. (2012). *Poverty and food security in Afghanistan: Analysis based on the national risk and vulnerability assessment of 2007/08*. Retrieved from.
Ishaq, A., Khalid, M., & Ahmad, E. (2018). *Food insecurity in Pakistan: A region-wise analysis of trends*. Retrieved from.
Jabeen, N., Farwa, U., & Jadoon, M. (2017). Urbanization in Pakistan: A governance perspective. *Journal of the Research Society of Pakistan, 54*(1), 127–136.
Jiang, L., & O'Neill, B. C. (2017). Global urbanization projections for the shared socioeconomic pathways. *Global Environmental Change Part A, 42*, 193–199.
Jones, B., & O'Neill, B. C. (2016). Spatially explicit global population scenarios consistent with the shared Socioeconomic Pathways. *Environmental Research Letters, 11*(8), Article 084003.
Kannan, M. (2015). *Radcliff line-the Indo-Pak border: Its geopolitical implications in the adjacent districts of Rajasthan*.
Kelso, N. V., & Patterson, T. (2010). Introducing natural earth data-naturalearthdata. com. *Geographia Technica, 5*(82-89), 25.
Klein Goldewijk, K., Beusen, A., & Janssen, P. (2010). Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene, 20*(4), 565–573.
Klein Goldewijk, K., Beusen, A., Van Drecht, G., & De Vos, M. (2011). The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography, 20*(1), 73–86.
Kok, K., Pedde, S., Gramberger, M., Harrison, P. A., & Holman, I. P. (2019). New European socio-economic scenarios for climate change research: Operationalising concepts to extend the shared socio-economic pathways. *Regional Environmental Change, 19*(3), 643–654.
Kraas, F. (2007). Megacities and global change in east, southeast and South Asia. *Asien, 103*(4), 9–22.
Kummu, M., Taka, M., & Guillaume, J. H. (2018). Gridded global datasets for gross domestic product and Human Development Index over 1990–2015. *Scientific Data, 5*, Article 180004.
Laghari, A., Vanham, D., & Rauch, W. (2012). The Indus basin in the framework of current and future water resources management. *Hydrology and Earth System Sciences, 16*(4), 1063.
Liangshu, L. (2002). *Outline of China's food and nutrition development (2001-2010)*. Retrieved from http://www.gov.cn/gongbao/content/2001/content_61214.htm.
Lutz, A. F., Immerzeel, W., Kraaijenbrink, P., Shrestha, A. B., & Bierkens, M. F. (2016). Climate change impacts on the upper Indus hydrology: Sources, shifts and extremes. *PloS One, 11*(11), Article e0165630.
Lutz, A. F., ter Maat, H. W., Wijngaard, R. R., Biemans, H., Syed, A., Shrestha, A. B., … Immerzeel, W. W. (2019). South Asian river basins in a 1.5 C warmer world. *Regional Environmental Change, 19*(3), 833–847.
Malpezzi, S. (2013). Population density: Some facts and some predictions. *Cityscape, 15*(3), 183–202.
Molden, D. J., Vaidya, R. A., Shrestha, A. B., Rasul, G., & Shrestha, M. S. (2014). Water infrastructure for the Hindu kush himalayas. *International Journal of Water Resources Development, 30*(1), 60–77.
Momblanch, A., Papadimitriou, L., Jain, S. K., Kulkarni, A., Ojha, C. S., Adeloye, A. J., … Holman, I. P. (2019). Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *The Science of the Total Environment, 655*, 35–47.
Mukherji, A., Scott, C., Molden, D., & Maharjan, A. (2018). Megatrends in Hindu Kush Himalaya: Climate change, urbanisation and migration and their implications for water, energy and food. *Assessing global water megatrends* (pp. 125–146). Springer.
Murakami, D., & Yamagata, Y. (2019). Estimation of gridded population and GDP scenarios with spatially explicit statistical downscaling. *Sustainability, 11*(7), 2106.
Mustafa, D., & Sawas, A. (2013). Urbanisation and political change in Pakistan: Exploring the known unknowns. *Third World Quarterly, 34*(7), 1293–1304.
Narula, K., Reddy, B. S., Pachauri, S., & Dev, S. M. (2017). Sustainable energy security for India: An assessment of the energy supply sub-system. *Energy Policy, 103*, 127–144.
NIN. (2011). *Dietary guidelines for Indians: A manual*. Retrieved from.
O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., … Kok, K. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change Part A, 42*, 169–180.
O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., … van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change, 122*(3), 387–400.
OSM. (2015). *OpenStreetMap*.
Parry, J.-E. (2016). *The vulnerability of Pakistan's water sector to the impacts of climate change: Identification of gaps and recommendations for action*. International Institute for Sustainable Development.
Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature, 540*(7633), 418–422.
Rao, N. D., Min, J., & Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nature Energy, 4*(12), 1025–1032.
Rasul, G. (2014). Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environmental Science & Policy, 39*, 35–48.
Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development, 18*, 14–25.

Reimann, L., Merkens, J.-L., & Vafeidis, A. T. (2018). Regionalized shared Socioeconomic Pathways: Narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change, 18*(1), 235–245.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., … Fricko, O. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change Part A, 42*, 153–168.

Richey, A. S., Thomas, B. F., Lo, M. H., Reager, J. T., Famiglietti, J. S., Voss, K., … Rodell, M. (2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research, 51*(7), 5217–5238.

Roy, J., Moors, E., Murthy, M., Prabhakar, S., Khattak, B. N., Shi, P., … Chitale, V. (2019). Exploring futures of the Hindu Kush Himalaya: Scenarios and pathways. *The Hindu Kush Himalaya assessment* (pp. 99–125). Springer.

Samir, K., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change Part A, 42*, 181–192.

Siddiqui, T., Bhagat, R. B., Banerjee, S., Liu, C., Sijapati, B., Memon, R., … Arif, G. M. (2019). Migration in the Hindu Kush Himalaya: Drivers, consequences, and governance. *The Hindu Kush Himalaya assessment* (pp. 517–544). Springer.

Tiwari, P. C., & Joshi, B. (2015). Climate change and rural out-migration in Himalaya. *Change and Adaptation in Socio-Ecological Systems, 2*(1).

UN. (2015). *The world population prospects: 2015 revision retrieved from New York*.

van Huijstee, J., van Bemmel, B., Bouwman, A., & van Rijn, F. (2018). *Towards an urban preview*.

Vinca, A., Parkinson, S., Riahi, K., Byers, E., Siddiqi, A., Muhammad, A., … Magnuszewski, P. (2020). Transboundary cooperation a potential route to sustainable development in the Indus basin. *Nature Sustainability*, 1–9.

Wada, Y., Vinca, A., Parkinson, S., Willaarts, B. A., Magnuszewski, P., Mochizuki, J., … Byers, E. (2019). Co-designing indus water-energy-land futures. *One Earth, 1*(2), 185–194.

Wanders, N., Wada, Y., & Van Lanen, H. (2015). Global hydrological droughts in the 21st century under a changing hydrological regime. *Earth System Dynamics, 6*(1), 1–15.

Weitz, N., Nilsson, M., & Davis, M. (2014). A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs. *SAIS Review of International Affairs, 34*(2), 37–50.

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (2018). *The Hindu Kush Himalaya assessment*. Springer.

Wijngaard, R. R., Biemans, H., Lutz, A. F., Shrestha, A. B., Wester, P., & Immerzeel, W. W. (2018). Climate change vs. Socio-economic development: Understanding the future South Asian water gap. *Hydrology and Earth System Sciences, 22*(12), 6297–6321.

Yang, Y. E., Ringler, C., Brown, C., & Mondal, M. A. H. (2016). Modeling the Agricultural Water–Energy–Food Nexus in the Indus River Basin, Pakistan. *Journal of Water Resources Planning and Management, 142*(12), Article 04016062.

Yillia, P. T. (2016). Water-energy-food nexus: Framing the opportunities, challenges and synergies for implementing the SDGs. *Österreichische Wasser-und Abfallwirtschaft, 68*(3–4), 86–98.