nature portfolio

https://doi.org/10.1038/s41558-022-01355-z

Supplementary information

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South Asian agriculture increasingly dependent on meltwater and groundwater

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Selection of climate change scenarios

Because there is a trade-off in the number of scenarios that can be included and the spatial and temporal resolution and level of physical detail that can be achieved for a scenario analysis we made a selection the number of RCP/SSP combination included and the number of downscaled GCM runs included. We have chosen to combine the RCP4.5 with SSP1 as our lower end scenario because it is at the moment more plausible that a climate scenario in the range of RCP4.5 can be reached compared to the RCP2.6 pathway. RCP2.6 is representative of the low end of the scenario literature in terms of emissions and radiative forcing[1]. It requires an immediate -counting from the moment of publication of the RCPs in 2011- drastic decline of emissions followed by ongoing carbon sequestration in the second half of the 21st century. The trend in emissions over the past decade has however pointed in the opposite direction[2] which has reduced the time to act to realize a RCP2.6 pathway by two thirds[3]. At the same time future emissions expected to come from existing capital are still large[4,5], and climate pledges to date are insufficient to achieve a 1.5 or 2.0 °C global warming scenario consistent with RCP2.6[6]. With our study we aim to present robust, realistic projections which can guide adaptation and therefore we choose not to include RCP2.6 in the climate model ensemble. By including RCP4.5 and RCP8.5 we cover a wide range of possible climatic futures. We are aware of the debate around assuming RCP8.5 as a 'business as usual' scenario[7], and present RCP8.5 scenarios as the most extreme case and refrain from labeling this scenario as 'business as usual'. For each RCP we downscaled four GCM runs which represent the entire pool of GCM runs in the CMIP5 ensemble in terms of the range in future projections for climatic means and climatic extremes, while at the same time ensuring acceptable skill in simulating the historical climate over our region of interest[8]. Note that in this approach GCM runs selected for one RCP are not necessary selected for the other RCP. In our results, in several figures we show future projected impacts as an ensemble mean and ensemble range as error bars. In other figures we show impacts for the individual simulations (i.e. 'spaghetti plots'), which the limited number of simulations included in each ensemble allows us to do. The real world will not evolve like an ensemble mean, but will behave more like an individual simulation[9], and each shown simulation is then a physically consistent possible future scenario. Although our approach is essentially top-down, showing the individual simulations is also more in line with the more recently developed approaches of using 'storylines' or 'tales' to represent uncertainty in climate change studies[10,11].

Contributions of meltwater to runoff

Different methods are used to estimate the contribution of glacier melt and snowmelt to total runoff and the quantification is a challenging problem[12,13]. We use a high resolution spatially distributed cryospheric-hydrological model to separate the runoff components[14]. We force the model with precipitation forcing that is corrected for the common underestimate of high mountain precipitation[15], and calibrate the model parameters related to glacier melt processes and snowmelt processes separately to remote sensing derived glacier mass balance and snow cover to avoid the often faced equifinality problems where meltwater compensates for the simulated underestimate in runoff from other sources in hydrological modelling of high mountain environments[16]. In Table S3 we compare our results to other studies in the region covering a range of spatial scales and approaches. We conclude that the contributions we find are well in the range of what other studies found. In terms of scale the studies by refs.[17,18] are most comparable to our study. Compared to ref.[17], our results are in similar range. Compared to ref.[18] results for the high altitude Indus basin are similar. In particular for the high altitude Brahmaputra basin results differ where ref.[18] indicates higher meltwater contributions.

Groundwater depletion

We assume groundwater to be used for irrigation when surface water is not available. Because we do not include a groundwater model including lateral groundwater flow, groundwater depletion is estimated for each individual grid cell as the difference between groundwater withdrawal and recharge (as in ref. [21]). Since we do not simulate lateral groundwater flows and groundwater heads, we cannot estimate the economic and/or physical limits to groundwater pumping and assume unlimited groundwater availability under each grid cell. Therefore, our estimates of non-renewable groundwater abstractions, in particular at the individual grid cell level, should be considered as a maximum estimate.

With this study we cannot assess how much groundwater is available. We do make the distinction in renewable and non-renewable groundwater abstractions to provide an indication of what is feasible in the long run. The total volume in the top 200 m of the Indo-Gangetic aquifer is estimated at 30,000 ± 14,000 km^3 (ref. [22]). Our simulated depletion rate for 2071-2100 for the RCP8.5-SSP3 ensemble mean averaged over the Indo-Gangetic aquifer is 95 km^3 yr^{-1} or up to 8550 km^3 cumulatively over 2011-2100. This indicates that the simulated rates fall well within what is theoretically possible. In reality, technically or economically feasible abstractions will be lower than what is theoretically possible, with pumping costs increasing with depth. For certain regions/seasons/years/crops it may not be worthwhile to irrigate anymore when groundwater tables drop. These factors are not included in our assessment. We rather show an indication of future increasing dependency on non-renewable groundwater as a baseline for adaptation efforts.

In a recent study on global groundwater pumping which did take into account physical limits to pumping[23], the simulations show large regions over the Indo-Gangetic plains with cumulative groundwater depletion rates over 25 m for 1960-2099 (RCP8.5). The cited study did not account for increases in irrigated areas, as we did include, but only assessed the effect of climate change. In this context our estimates with over 20 m of cumulative groundwater depletion for 2011-2100 in the RCP8.5-SSP3 ensemble at some locations are high, but not unrealistic upper estimates.

A future improvement could be the inclusion of a groundwater model in the assessment to estimate physical limits to abstractions, as well as inclusion of analysis of economic groundwater abstraction feasibility.

Supplementary Figures

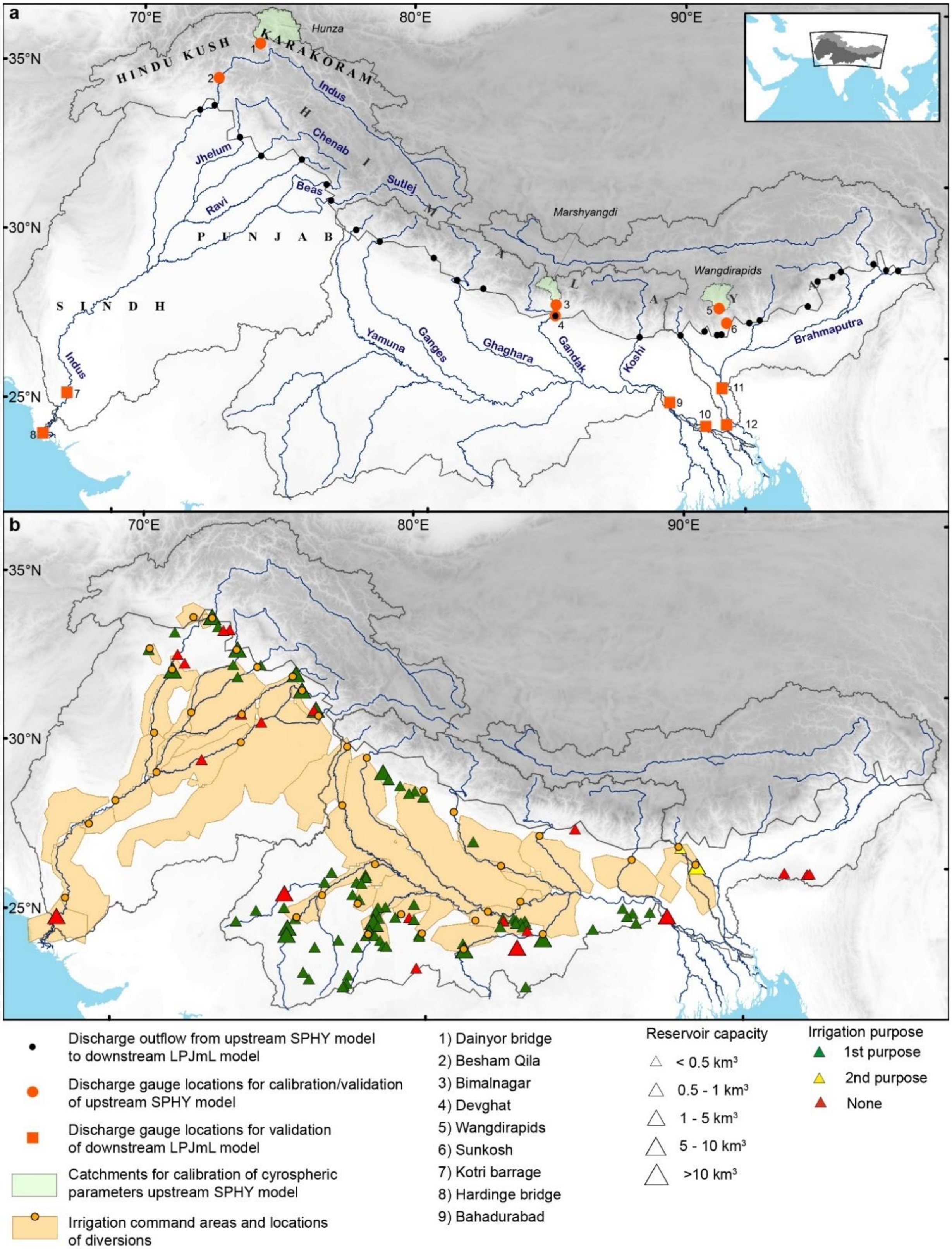

Figure S1: a) Map indicating locations where simulated discharge from upstream SPHY model feeds into downstream LPJmL model, locations of discharge gauges and catchments used for calibration/validation, geographical names of regions, mountain ranges and rivers[24] referred to in the main text. b) Map indicating reservoirs[25], irrigation command areas and locations of diversions to command areas. Source of background digital elevation model: GTOPO30.

Supplementary Tables

Table S1: Basin averaged climate change signals of downscaled climate change scenarios used in this study.

			ΔT 2071-2100 vs. 1981-2010 (°C)			ΔP 2071-2100 vs. 1981-2010 (%)		
RCP	**Scenario**	**GCM run**	Indus	Ganges	Brahmaputra	Indus	Ganges	Brahmaputra
RCP4.5	Cold, wet	BNU-ESM_r1i1p1	2.1	1.9	2.0	15.7	18.6	12.3
	Cold, dry	inmcm4_r1i1p1	1.1	1.2	1.2	6.9	21.0	13.1
	Warm, dry	CMCC-CMS_r1i1p1	2.9	2.5	2.5	-0.7	3.3	5.3
	Warm, wet	CSIRO-Mk3-6-0_r4i1p1	3.5	3.2	2.9	24.1	22.7	3.6
RCP8.5	Cold, wet	bcc-csm1-1_r1i1p1	3.6	3.1	3.1	21.7	23.4	18.8
	Cold, dry	inmcm4_r1i1p1	2.7	2.6	2.6	15.8	29.0	23.2
	Warm, dry	CMCC-CMS_r1i1p1	5.6	4.9	4.7	-8.6	-2.7	11.2
	Warm, wet	CanESM2_r3i1p1	5.2	4.2	4.4	10.3	22.4	35.0

Table S2: Simulated average annual withdrawal, and blue water consumption for irrigation during 1981-2010.

	Indus	**Ganges**	**Brahmaputra**
Irrigation withdrawal ($km^3\ yr^{-1}$)	498	301	14
Irrigation blue water consumption ($km^3\ yr^{-1}$)	104	91	4
Consumed fraction of withdrawal	0.21	0.30	0.27

Table S3: Model performance indicators for 9 locations for calibration/validation to observed discharge. Based on Table 4 in ref.[26] and Supplementary Table 1 in ref.[27].

Station	**ID in Figure S1**	**Period**	**Nash-Sutcliffe Efficiency**	**Bias (%)**
Dainyor bridge (calibration)	1	2000-2005	0.60	-30.9
Dainyor bridge (validation)	1	2008-2010	0.74	-16.0
Besham Qila (calibration)	2	2000-2005	0.69	-9.2
Besham Qila (validation)	2	2006-2008	0.62	2.6
Bimalnagar (calibration)	3	2000-2005	0.78	-10.0
Bimalnagar (validation)	3	2007-2009	0.75	-12.9
Devghat (calibration)	4	2000-2005	0.84	1.8
Devghat (validation)	4	2007-2009	0.82	3.1
Wangdirapids (calibration)	5	1998-2003	0.76	-4.0
Wangdirapids (validation)	5	2004-2008	0.75	-8.7
Sunkosh (calibration)	6	1998-2003	0.68	17.5
Sunkosh (validation)	6	2004-2008	0.74	8.2
Kotri Barrage (validation	7	1981-2003	-0.47	237.0
Hardinge Bridge (validation)	8	2001-2010	0.74	33.9
Bahadurabad (validation)	9	1981-2008	0.63	5.1

Table S4: Comparison of streamflow contributions to other studies.

Location and reference	**Period cited study**	**Method for contribution source determination cited study**	**Meltwater contribution cited study**	**Meltwater contribution 1981-2010 this study**
Indus basin above 2000 m[18]	2001-2014	Temperature index melt model	76%	83%
Ganges basin above 2000 m[18]	2001-2014	Temperature index melt model	48%	29%
Brahmaputra basin above 2000 m[18]	2001-2014	Temperature index melt model	74%	34%
Indus basin above 2000 m[17]	1979-2019	Temperature index melt model	69%	83%
Ganges basin above 2000 m[17]	1979-2019	Temperature index melt model	29%	29%
Brahmaputra basin above 2000 m[17]	1979-2019	Temperature index melt model	21%	34%
Chamkar Chhu, Brahmaputra basin[28]	Mar, Jun, Aug, Oct 2016	Stable isotope tracers in mixing model	48%	39%
Sutlej River, Indus basin[29]	2000-2012	Temperature index melt model	45%	68%
Langtang river basin, Ganges basin[30]	Multiple single dates in different seasons	Hydrochemistry and isotope tracers in mixing model	15-77%	30%
Langtang basin, Ganges basin[31]	2012-2013	Glacio-hydrological model	66%	30%
Beas river, Indus basin[32]	2010-2011	Isotope analysis and hydrological modelling	50% (isotope analysis) / 52% (hydrological modelling)	60%
Chandra river, Indus basin[33]	25 Apr – 25 Sep 2017	Tracer based	61%	74%
Besham Qila, Indus basin[34]	1969-2010	Hydrograph separation	70%	90%
Hunza river, Indus basin[34]	1966-2010	Hydrograph separation	74%	88%
Lhasa river, Brahmaputra basin[35]	1971-2000	Hydrological model	44%	25%

Table S5: Key model parameters.

Upstream SPHY model

Parameter	**Units**	**UIB**	**UGB**	**UBB**
Glaciers				
DDFG	mm °C day^{-1}	6.3	8.5	5.0
DDFDG	mm °C day^{-1}	3.0	6.5	3.5
Snow				
Tcrit	°C	0	0	0
SnowSC	mm mm^{-1}	0.5	0.2	0.5
DDFS	mm °C day^{-1}	6.0	7.5	4.1
Subl3Rate	mm day^{-1}	1.5	3.2	1.25
Rainfall-runoff and routing				
alphaGW	-	0.005	0.062	0.005
deltaGW	day	1	10	1
Kx	-	0.955	0.93	0.96
GlacF	-	0.6	0.9	0.9
RootDepth	mm	800	653	600
SubDepth	mm	2766	2679	2705

Downstream LPJmL model

Parameter	**Units**	**Value**
Topsoil depth	mm	300
Soil volume fraction	-	0.7
Open canal conveyance efficiency, soil type sand	-	0.70
Open canal conveyance efficiency, soil type loam	-	0.75
Open canal conveyance efficiency, soil type clay	-	0.80
Surface irrigation distribution uniformity scalar	-	1.15
Maximum leaf area index	-	5

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