Supplement of Hydrol. Earth Syst. Sci., 21, 791–804, 2017
http://www.hydrol-earth-syst-sci.net/21/791/2017/
doi:10.5194/hess-21-791-2017-supplement

Hydrology and Earth System Sciences
Open Access

Supplement of

Water scarcity under various socio-economic pathways and its potential effects on food production in the Yellow River basin

Yuanyuan Yin et al.

Correspondence to: Qiuhong Tang (tangqh@igsnrr.ac.cn)

Supplemental Methodology:

1. Bias correction methodology (Ho et al., 2012)

The bias correction methodology corrects the simulated raw annual runoff using the differences in the mean and variability between observations and the simulations in 1971-2000. In the simplest case, where the variability in observations and simulations is assumed to be the same -- the normal distribution, the annual runoff is simply shifted by the mean bias in the reference.

$$R_{BC}(t) = R_{RAW}(t) + \left(\overline{R_{O,REF}} - \overline{R_{M,REF}}\right) \qquad \text{(Equation 1)}$$

Where $R_{BC}(t)$ is the bais-corrected simulated runoff, $R_{RAW}(t)$ is raw simulated runoff for future period, $\overline{R_{O,REF}}$ is the mean of the observation in 1971-2000, $\overline{R_{M,REF}}$ is the mean of the simulated runoff in 1971-2000.

However, it is possible to apply a more general form of this bias-correction method that corrects not only the mean values but also the temporal variability of the model output in accordance with the observations (Ho et al., 2012),

$$R_{BC}(t) = \overline{R_{O,REF}} + \frac{\sigma_{O,REF}}{\sigma_{T,REF}}\left(R_{RAW}(t) - \overline{R_{O,REF}}\right) \qquad \text{(Equation 2)}$$

Where $\sigma_{T,REF}$ and $\sigma_{O,REF}$ represent the standard deviation of the simulated runoff and observations in the reference period, respectively.

Supplemental Figures:

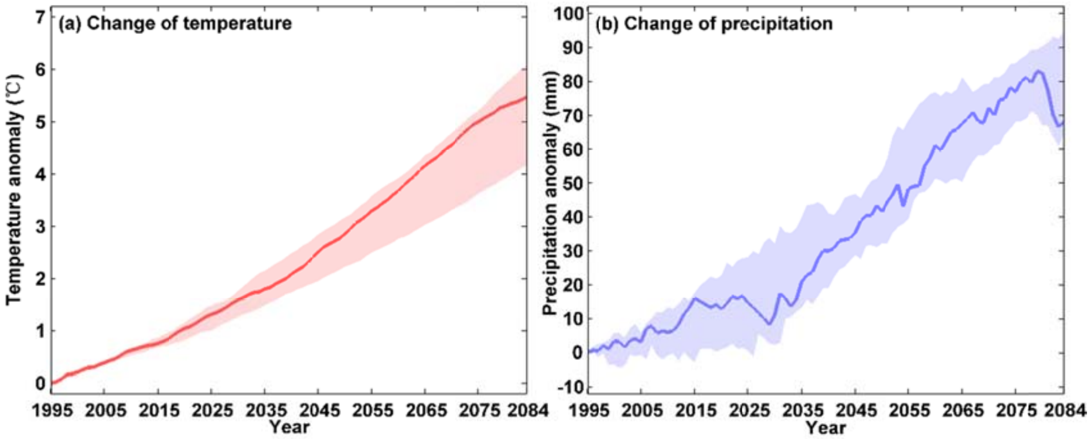

Figure S1 Change of (a) temperature and (b) precipitation from 1995-2084 with respect to 1981-2010 in the YR basin under the RCP 8.5 emission scenario. The red (blue) shaded area denotes the interquartile range for the temperature (precipitation) anomaly and the solid line shows the median of the GCMs.

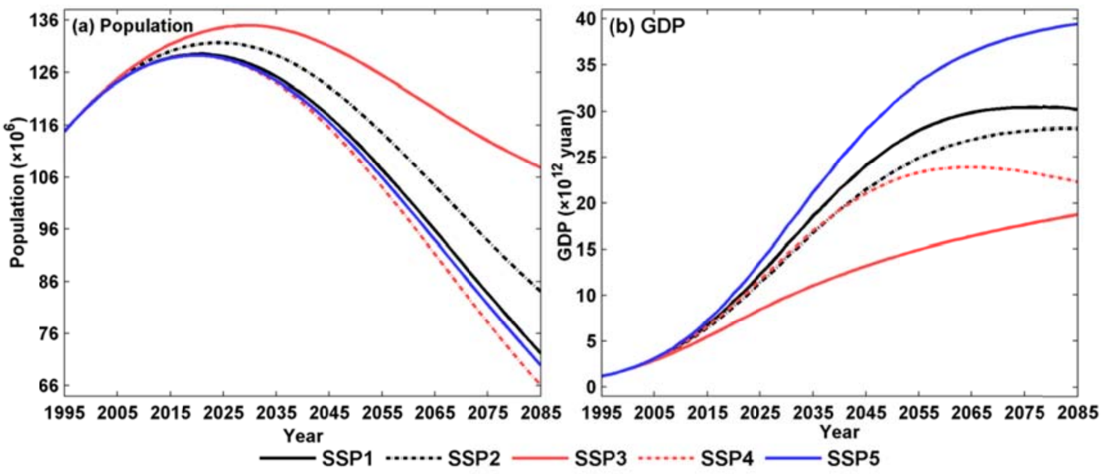

Figure S2 Population and gross domestic gross (GDP) from 1995-2085 in the YR basin under SSP1, SSP2, SSP3, SSP4 and SSP5.

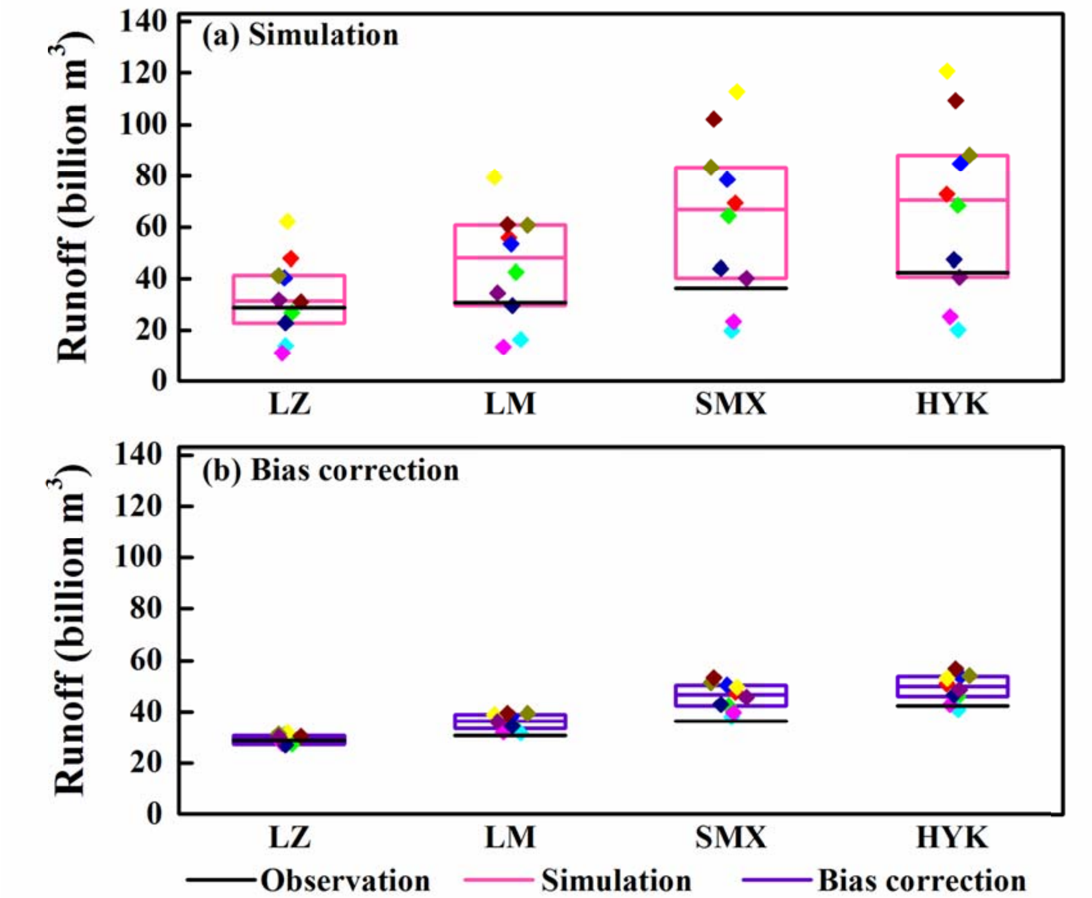

Figure S3 Comparison between observation and simulation and bias corrected simulation at four runoff sits in the YL basin. LZ, LM, SMX, and HYK are short for Lanzhou, Longmen, Sanmenxia, and Huayuankou, respectively.

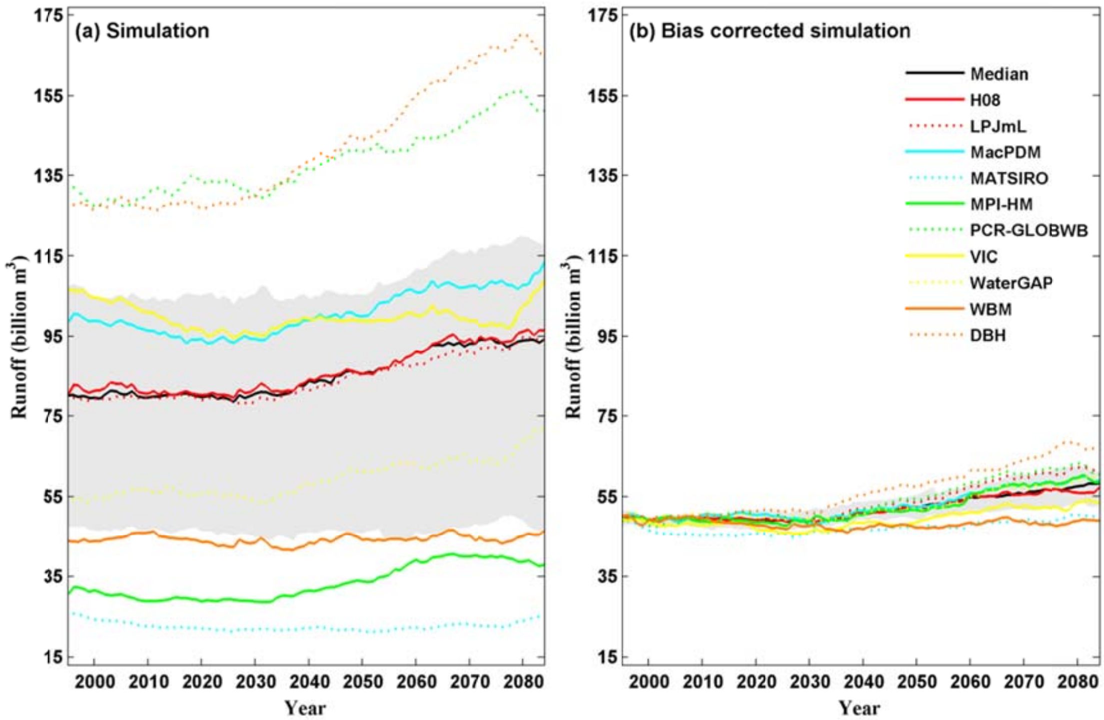

Figure S4 Simulated runoff (a) and the bias corrected runoff (b) during 1995-2084 in the YR basin. The shaded band denotes the inter-quartile range and the black solid line shows the median of 50 GCM-GGHM pairs. The solid and dashed colored lines represent the median of the five GCMs for each GGHM.

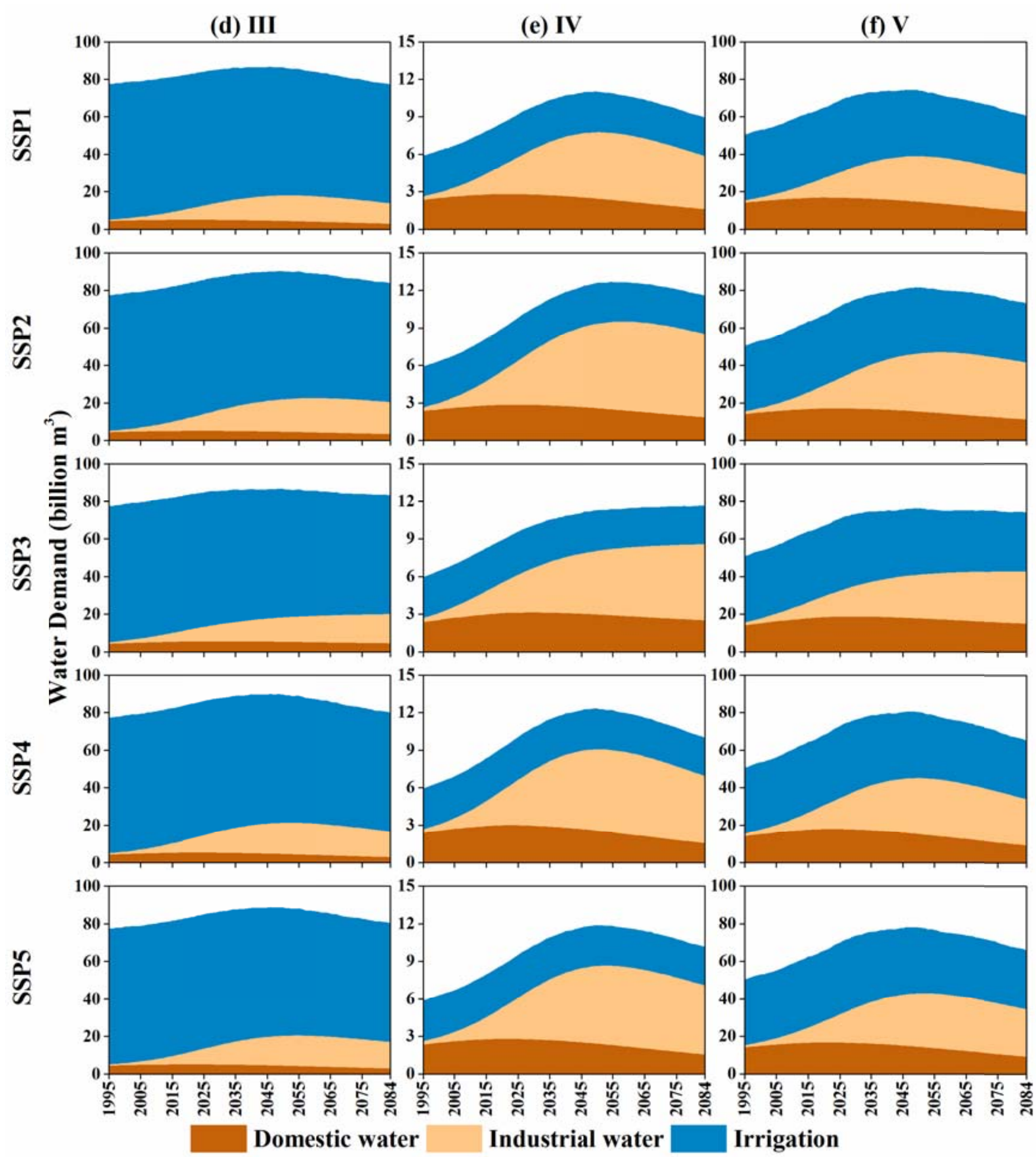

Figure S5 Estimated sectoral (domestic, industrial and irrigation) and total annual water demand (million m^3 yr^{-1}) in sub-basin III, IV and V from 1995 to 2085 during the 21st century.

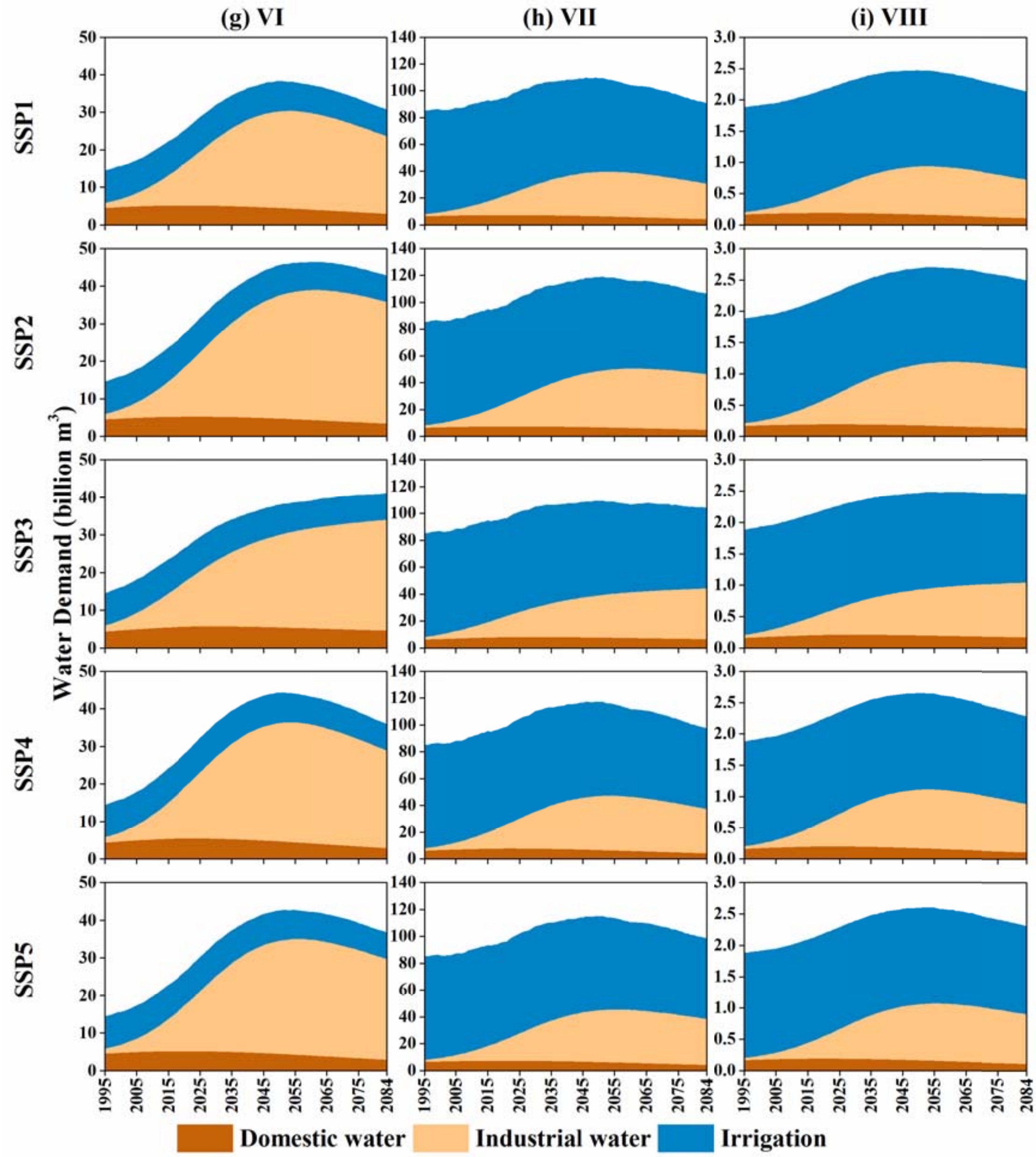

Figure S6 Estimated sectoral (domestic, industrial and irrigation) and total annual water demand (million m^3 yr^{-1}) in sub-basin VI, VII and VIII from 1995 to 2085 during the 21[st] century.

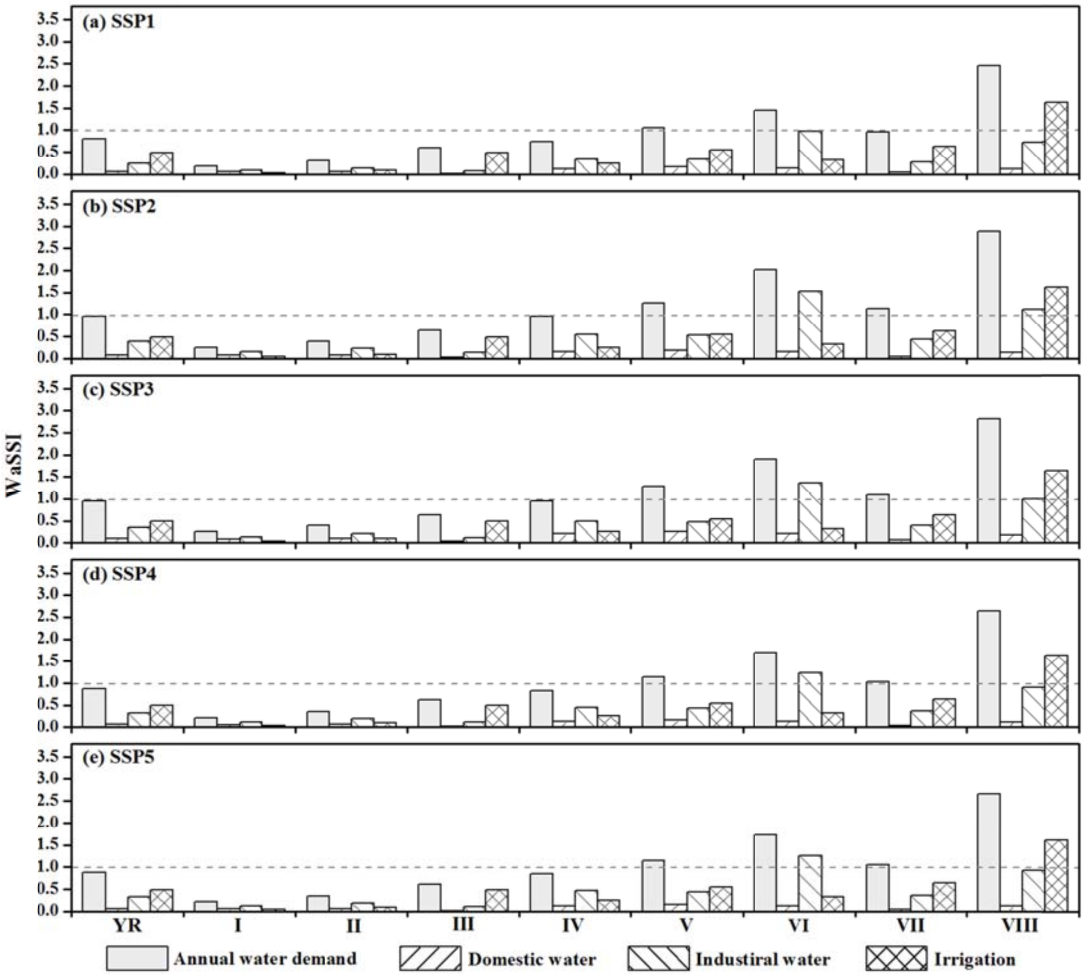

Figure S7 WaSSI calculated as the ratio of annual water demand and sectoral (domestic, industrial and irrigation) water withdrawals to annual water supply for the YR basin and eight sub-basins at the end of the 21st century under the five different SSPs. The annual water supply was estimated with an RHWA value of 60% (RHWA60).

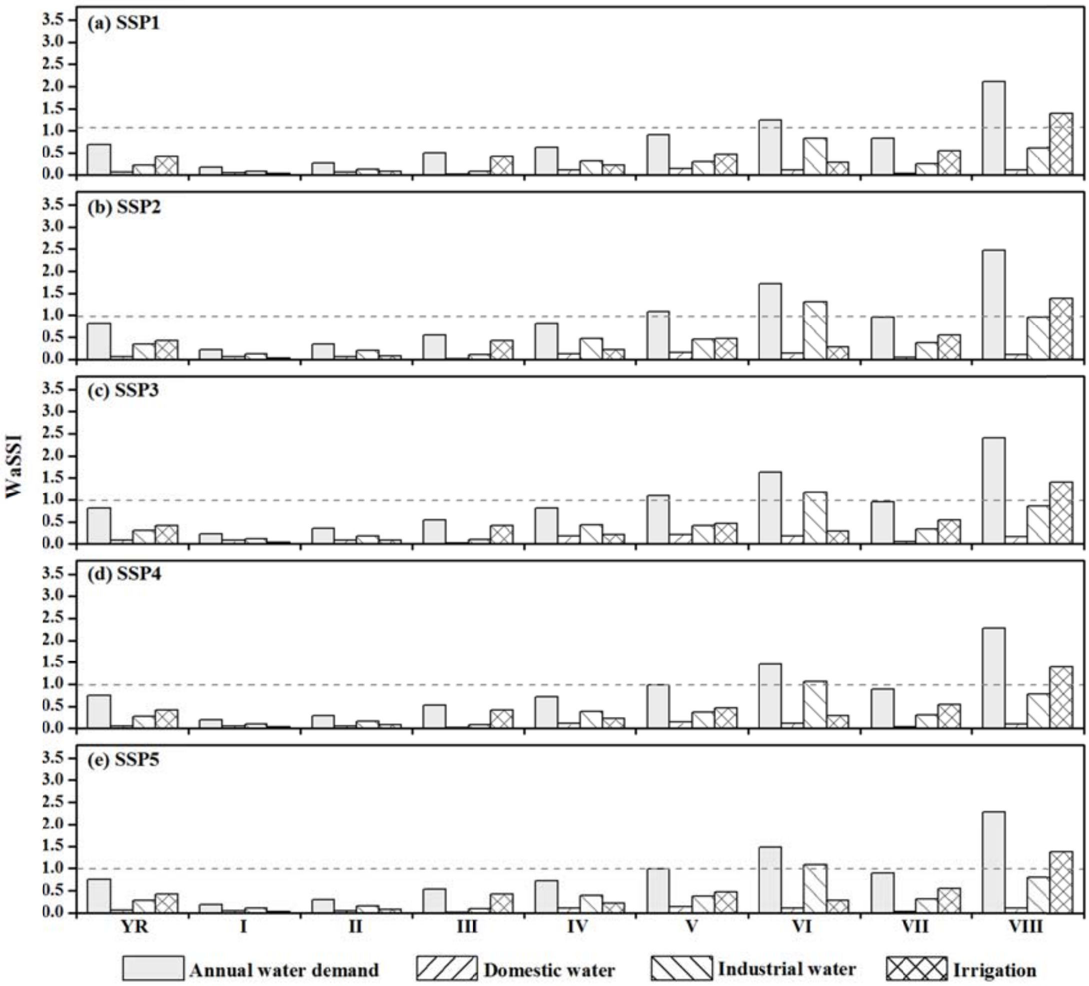

Figure S8 WaSSI calculated as the ratio of annual water demand and sectoral (domestic, industrial and irrigation) water withdrawals to annual water supply for the YR basin and eight sub-basins at the end of the 21st century under the five different SSPs. The annual water supply was estimated with an RHWA value of 70% (RHWA70).

Supplemental Tables:

Table S1 Main characteristics of the global gridded hydrological models (GGHMs) used in this study.

Model name	Energy balance	Evaporation scheme [a]	Runoff scheme [a]	Vegetation dynamics	References
DBH	Yes	Energy balance	Infiltration excess	No	Tang et al. (2007, 2008)
H80	Yes	Bulk formula	Saturation excess, no-linear	No	Hanasaki et al. (200a, 2008b)
LPJmL	No	Priestley-Taylor	Saturation excess	Yes	Bondeau et al. (2007); Rost et al. (2008)
MacPDM	No	Penman-Monteith	Saturation excess, no-linear	No	Arnell (1999); Gosling and Arnell (2011)
MATSIRO	Yes	Bulk formula	Infiltration excess, saturation excess, groundwater	No	Takata et al. (2003); Pokhrel et al. (2012)
MPI-HM	No	Penman-Monteith	Saturation excess, no-linear	No	Hagemann et al. (2003); Stacke et al. (2012)
PCR-GLBWB	No	Hamon	Saturation excess, Beta function	No	Wada et al. (2010); Van Beek et al (2001); Wada et al. (2011)
VIC	Only for snow	Penman-Monteith	Saturation excess, no-linear	No	Liang et al. (1994); Lohmann and Raschke (1988)
WaterGAP	No	Priestley-Taylor	Beta function	No	Döll et al. (2012); Flörke et al. (2013)
WBM	No	Hamon	Saturation excess	No	Vörösmarty et al. (1998); Wisser et al. (2010)

Note: a Bulk formula: Bulk transfer coefficients are used when calculating turbulent heat fluxes.

b Non-linear: Subsurface runoff is a non-linear function of soil moisture.

Table S2 Main characteristics of the global gridded crop models (GGCMs) used in this study.

Model name	Evapo-transpiration	Irrigation [a, b]	Crops	References
EPIC	Penman-Monteith	90/100/500/50/20 [h] maximum applied irrigation: 500 mm yr^{-1}	Maize, wheat, soybean, rice, barley, managed grass, millet, rapeseed, sorghum, sugarcane, drybean, cassava, cotton, sunflower, groundnut	Williams (1995); Izaurralde et al. (2006)
GEPIC	Penman-Monteith	90/100/20 00/1000/0 .01[h]	Maize, wheat, soybean, rice	Williams (1990); Liu et al. (2007)
LPJmL	Priestley-Taylor	300/90/10 0/varies [g]	Maize, wheat, soybean, rice, millet, cassava, sugar beet, field pea, rapeseed, sunflower, groundnut, sugarcane	Bondeau et al. (2007); Fader et al. (2010)
LPJ-GUESS	Priestley-Taylor	200/90/10 0/100 [g]	Maize, wheat, soybean, rice	Bondeau et al. (2007); Smith et al. (2011)
pDSSAT	Priestley-Taylor	40/80/100/75 [g] rice: 30/50/100 /100 [g]	Maize, wheat, soybean, rice	Elliott et al. (2014); Jones et al. (2013)
PEGASUS	Priestley-Taylor	40/90/100/100 [g]	Maize, wheat, soybean	Deryng et al. (2011)

Note: a Irrigation rules: IMDEP(cm): Depth of soil moisture measured; ITHRL(%): Critical lower soil moisture threshold to trigger irrigation event; ITHRU(%): Upper soil moisture threshold to stop irrigation; IREFF(%): Irrigation application efficiency

b Irrigation rules: EPIC and GEPIC models: BIR(%): Water stress in crop to trigger automatic irrigation; EFI(%): Irrigation efficiency - runoff from irrigation water; VIMX(mm): Maximum of annual irrigation volume; ARMX(mm): Maximum of single irrigation volume allowed; ARMN(mm): Minimum of single irrigation volume allowed

Table S3 Overview of global climate models (GCMs) used in this study.

	Name	Institute	References
GCMs	HadGEM2-ES	Met Office Hadley Centre	Jones et al. (2011)
	IPSL-CM5A-LR	Institute Pierre-Simon Laplace	Mignot et al. (2013)
	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	Watanabe et al. (2011)
	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	Dunne et al. (2012, 2013)
	NorESM1-M	Norwegian Climate Centre	Bentsen et al. (2013); Iversen et al. (2013)

Table S4 Change rate for domestic water intensity (L person^{-1} day^{-1} year^{-1}) (Hanasaki et al., 2013)

		High efficiency (HE)	Medium efficiency (HE)	Low efficiency (HE)
per captia GDP<2000 USD	200≤i_{dom}	-2 (200≤i_{dom})	0	2 (i_{dom}<600)
	i_{dom}<200	2 (i_{dom}<200)	2 (i_{dom}<300)	2 (i_{dom}<400)
2000 USD≤per captia GDP		-2 (200≤i_{dom})	0	2 (i_{dom}<800)

Reference:

Arnell, N.: A simple water balance model for the simulation of streamflow over a large geographic domain, J. Hydrol., 217: 314-335, 1999.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevag, A., Seland, Ø.,Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., and Kristjansson, J. E.: The Norwegian Earth System Model, NorESM1-M – part 1: Description and basic evaluation of the physical climate, Geosci. Model Dev., 6, 687-720, 2013.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Muller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol., 13, 679-706, 2007.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M, and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol., 13, 679-706, 2007.

Deryng, D., Sacks, W. J., Barford, C. C., and Ramankutty, N.: Simulating the effects of climate and agricultural management practices on global crop yield, Global Biogeochem. Cy., 25(2), GB2006, doi: 10.1029/2009GB003765, 2011.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., and Scanlon, B. R.: Impact of water withdrawals from groundwater and surface water on continental water storage variations, J. Geodyn., 59-60, 143-156, 2012.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., Stouffer, R. J., Cooke, W., Dunne, K. A., Harrison, M. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Phillipps, P. J., Sentman, L. T., Samuels, B. L., Spelman, M. J., Winton, M., Wittenberg, A. T., and Zadeh, N.: GFDL's ESM2 global coupled climate–carbon earth system models, part 1: Physical formulation and baseline simulation characteristics, J. Climate, 25, 6646-6665, 2012.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., and Zadeh, N.: GFDL's ESM2 global coupled climate–carbon earth system models, part 2: Carbon system formulation and baseline simulation characteristics, J. Climate, 26, 2247-2267, 2013.

Elliott, J., Kelly, D., Chryssanthacopoulos, J., Glotter, M., Jhunjhnuwala, K., Best, N., Wilde, M., and Foster, I.: The Parallel System for Integrating Impact Models and Sectors (pSIMS), Environ. Modell. Softw., 62, 509-516, 2013.

Fader, M., Rost, S., Muller, C., Bondeau, A., and Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns, J. Hydrol, 384, 218-231, 2010.

Flörke M., Kynast, E., Barlund, I., Eisner, S., Wimmer, F., and Alcamo, J.: Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study, Global Environ. Chang., 23, 144-156, 2013.

Gosling, S. N., and Arnell. N. W.: Simulating current global river runoff with a global hydrological model: Model revisions, validation, and sensitivity analysis, Hydrol. Process., 25: 1129-1145, 2011.

Hagemann, S., and Dümenil, G. L.: Improving a subgrid runoff parameterization scheme for climate models by the use of high resolution data derived from satellite observations, Clim. Dynam, 21, 349-359, 2003.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., Takahashi, K., and Kanae, S.: A global water scarcity assessment under Shared Socio-economic Pathways – Part 1: Water use. Hydrol. Earth Syst. Sci., 17, 2375-2391, 2013.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, Hydrol. Earth Syst. Sc., 12, 1007-1025, 2008a.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 2: Applications and assessments, Hydrol. Earth Syst. Sc., 12, 1027-1037, 2008b.

Ho, C., Stephenson, S., Collins, M., Freeo, C., and Brown, S.: Calibration strategies: A source of additional uncertainty in climate change projections, B. Am. Meteorol. Soc., 93(1):21-26, 2012.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J. B., Kirkevag, A., Seland, O., Drange, H., Kristjansson, J. E., Medhaug, I., Sand, M., and Seierstad, I. A.: The Norwegian Earth System Model, NorESM1-M – part 2: Climate response and scenario projections, Geosci. Model Dev., 6, 389-415, 2013.

Izaurralde, R.C., Williams, J. R., McGill, W. B., Rosenberg, N. J., and QuirogaJakas, M. C.: Simulating soil C dynamics with EPIC: Model description and testing against long-term data, Ecol. Model., 192(3-4), 362-384, 2006.

Jones, C. D., Huges, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J., Liddicoat, S., O'Connor, F. M., Andres, R. J., Bell, C., Boo, K., Bozzo, A., Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gary, L., Halloran, P. R., Hurtt, G., Ingram, W. J., Lanarque, J. F., Law, R. M., Meinshausen, M., Osprey, S., Palin, E. J., Chini, L., Raddatz, T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M.: The HadGEM2-ES implementation of CMIP5 centennial simulations, Geosci. Model Dev., 4, 543-570, 2011.

Jones, J.W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A., and Ritchie, J. T.: The DSSAT cropping system model, Eur. J. Agron., 18, 235-265, 2003.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99, 14415-14428, 1994.

Liu, J., Williams, J. R., Zehnder, A. J. B., and Hong, Y.: GEPIC–modelling wheat yield and crop water productivity with high resolution on a global scale, Agr. Syst., 94(2), 478-493, 2007.

Lohmann, D., and Raschke, E.: Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, Hydrolog. Sci. J., 43, 131-141, 1998.

Mignot, J., and Bony, S.: Presentation and analysis of the IPSL and CNRM climate models used in CMIP5, Clim. Dynam, 40(9), 2089-2089, 2013.

Pokhrel, Y., Hanasaki, N., Koirala, S., Cho, J., Yeh, P., Kim, H., Kanae, S., and Oki, T.: Incorporating anthropogenic water regulation modules into a land surface model. J. Hydrometeorol., 13: 255-269, 2012.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resour. Res., 44: 1-17, 2008.

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: Comparing two contrasting approaches within European climate space, Global Ecol. Biogeogr., 10, 621-637, 2001.

Stacke, T., and Hagemann, S.: Development and validation of a global dynamical wetlands extent scheme, Hydrol. Earth Syst. Sc., 9, 405-440, 2012.

Takata, K., Emori, S., and Watanabe, T.: Development of the minimal advanced treatments of surface interaction and runoff, Global Planet. Change, 38: 209-222, 2003.

Tang, Q., Oki, T., Kanae, S., and Hu, H.: Hydrological cycles change in the Yellow River Basin during the last half of the twentieth century, J. Climate, 21: 1790-1806, 2008.

Tang, Q., Oki, T., Kanae, S., and Hu, H.: The influence of precipitation variability and partial irrigation within grid cells on a hydrological simulation, J. Hydrometeorol., 8: 499-512, 2007.

Van Beek, L., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: 1. Water balance and water availability, Water Resour. Res., 47, W07517, doi: 10.1029/2010WR009791, 2011.

Vörösmarty, C. J., Federer, C. A., and Schloss, A. L.: Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling, J. Hydrol, 207, 147-169, 1998.

Wada, Y., van Beek, L., van Kempen, C., Reckman, J., Vasak, S., and Bierkens, M.: Global depletion of groundwater resources, Geophys. Res. Lett., 37, L20402, doi: 10.1029/1010GL044571, 2010.

Wada, Y., van Beek, L., Viviroli, D., Duee, H. H., Weingartner, R., and Bierkens, M.: Global monthly water stress: 2 Water demand and severity of water stress, Water Resour. Res., 47, W07518, doi: 10.1029/2010WR009792, 2011.

Watanabe, S., Hajima, T. Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise, T., Sato, H., Kato, E., Takata, K., Emori, S., and Kawamiya, M.: MIROC-ESM 2010: Model description and basic results of CMIP5-20c3m experiments, Geosci. Model Dev., 4, 845-872, 2011.

Williams, J. R.: EPIC-Erosion/Productivity Impact Calculator. United States Department of Agriculture Agricultural Research Service. Technical Bulletin Number 1768. Springfield, VA, 1990.

Williams, J. R.: The EPIC. In: Singh, V.P. (Ed.). Computer Models of Watershed Hydrology Water Resources Publications. Littleton, CO. pp. 909-1000 (Chapter 25), 1995.

Wisser, D., Fekete, B. M., Vorosmarty, C. J., and Schumann, A. H.: Reconstructing 20^{th} century global hydrography: A contribution to the Global Terrestrial Network- Hydrology (GTN-H), Hydrol. Earth Syst. Sc., 14, 1-24, 2010.