Global economic and food security impacts of demand-driven water scarcity - alternative water management options for a thirsty world

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Supplementary Material

1. Regional and sectoral aggregation

Table A-1 - RESCU-Water sectoral mapping

RESCU-Water sector	GTAP9Power sector
PDR_IRC – paddy rice irrigated	PDR paddy rice (disaggregated)
PDR_RFC – paddy rice rainfed	
WHT_IRC – wheat rice irrigated	WHT wheat (disaggregated)
WHT_RFC – wheat rice rainfed	
GRO_IRC – other grains irrigated	GRO other grains (disaggregated)
GRO_RFC – other grains rainfed	
V_F_IRC – veg&fruits irrigated	V_F vegetables & fruits (disaggregated)
V_F _RFC – veg&fruits rainfed	
OSD_IRC – oil seeds irrigated	OSD oil seeds (disaggregated)
OSD_RFC – oil seeds rainfed	
C_B_IRC – cane and beet irrigated	C_B cane & beet (disaggregated)
C_B_RFC – cane and beet rainfed	
PFB_IRC – plant fibres irrigated	PFB plant-based fibers (disaggregated)
PFB_RFC – plant fibres rainfed	
OCR_IRC – other crops irrigated	OCR other crops (disaggregated)
OCR_RFC – other crops rainfed	
LSTK – Livestock	CTL Cattle, OAP Animal products, RMK Raw milk, WOL wool
AGRO – Agriculture other	FRS forestry, FSH Fish
PCF – Processed food	OMT Meat products, VOL Vegetable oils, MIL Dairy products, PCR Processed rice, SGR Sugar, OFD Food products other, B_T Beverages and tobacco
M_M – Metals and minerals	NMM mineral products, I_S iron and steel, NFM non-ferrous metals, FMP metal products, OMN minerals
CHEM - Chemicals	CRP chemicals
PAP – Pulp and paper	PPP pulp and paper products
ENE - Energy	COA coal, OIL oil, GAS gas, P_C petroleum coal, ELY Electricity, GDT gas distribution, TnD Transmission and distribution

RESCU-Water sector	GTAP9Power sector
ELT – Electricity thermal	NuclearBL, CoalBL, GasBL, OilBL, OtherBL, GasP, OilP
ELN – Electricity non-thermal	WindBL, HydroBL, SolarP
MANU – Manufacturing	TEX Textiles, WEA Wearing apparel, LEA Leather products, LUM Wood products, PPP Paper products, CMT cement MVH motor vehicles, OTN transport equipment, ELE electric equipment, OME machinery, OMF manufactures, WTR water
IWT – Industrial Water	WTR – Water distribution
MWT – Municipal Water	
SERV – Other services	OSG Public Administration, CMN Communication, OFI Financial services, ISR Insurance, OBS Business services, ROS Recreational services
TRNS – Transport	OTP Transport, WTP Water Transport, ATP Air transport
CONS – Construction	CNS Construction, DWE Dwellings

Table A-2 - RESCU-Water regional mapping

RESCU-Water region	**GTAP-Power regions**
AUZ Australia and New Zealand	Australia, New Zealand, Rest of Oceania
SEA – South East Asia	Brunei, Cambodia, Indonesia, Laos, Myanmar, Philippines, Singapore, Thailand, Vietnam, Nepal, Rest of SE Asia
CNA- China	China, Hong Kong, Taiwan
NEA – North East Asia	Japan, Korea Republic of, Rest of East Asia*
SAS – South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia*
IND – India	India
CEA – Central Asia	Mongolia, Kazakhstan, Kirgizstan
MEA – Middle East Asia	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, UAE, Rest of Western Asia*
EUA – Eurasia	Belarus, Russia, Ukraine, Rest of Eastern Europe, Rest of Former Soviet Union*, Armenia, Azerbaijan, Georgia
NEU – Northern Europe	Belgium, Denmark, Estonia, Finland, Germany, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Sweden, Great Britain, Switzerland, Rest of EFTA*
SEU – Southern Europe	Austria, Cyprus, Czech Republic, France, Greece, Hungary, Italy, Malta, Portugal, Slovakia, Slovenia, Spain, Albania, Bulgaria, Croatia, Romania, Rest of Europe*
NAF – Northern Africa	Egypt, Morocco, Tunisia, Rest of North Africa*, Rest of Eastern Africa*

RESCU-Water region	GTAP-Power regions
CAFH – Central Africa	Benin, Burkina-Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Togo, South Central Africa*, Ethiopia, Kenya, Madagascar, Mauritius, Mozambique, Rwanda, Tanzania, Uganda
CAFD – Sahel	Rest of Western Africa*, Rest of Central Africa*, Senegal
SAF – Southern Africa	Malawi, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of South African Customs Union*
NOA – Canada	Canada, Rest of North America*
USA – United States	United States
NLAM – North Latin America	Mexico, Bolivia, Columbia, Ecuador, Peru, Venezuela, Rest of South America*, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America*, Dominican Republic, Jamaica, Puerto Rico, Trinidad Tobago, Caribbean*
BRA – Brazil	Brazil
SLAM – South Latin America	Argentina, Chile, Paraguay, Uruguay, Rest of the World*

Note: (*) aggregated regions in the GTAP database

2. Water representation in productive activities in RESCU-Water

The main evolution of the RESCU-Water model from the version used in [1] consists in the specification of water as an explicit economy-wide factor of production. In irrigated crop production (Figure A-1), water is employed as a perfect complement to irrigated land and irrigation equipment to form the irrigation-water-land *iwl* composite. The technical coefficient for water inputs in irrigation varies from across the eight crop classes in the model. Also, each of these three factors has a productivity parameter associated $\theta_{iwl,irc}^{LND}$ to enable the consideration of efficiency changes following e.g. changes in water field application methods. The production technology for rainfed crops remains unchanged (Figure A-2) from the previous version of the model. Irrigated and rainfed varieties of the same crop are treated as near perfect substitutes in final and intermediate demand through a CES specification with an elasticity of substitution equal to 10 (see [2]).

The use of water endowments into the other four self-abstracting industries SAI (livestock, thermo-electric, industrial water supply and municipal water supply) is introduced at the top level of the production function through a Leontief specification (Figure A-3). Similarly to crops, thermal and non-termal electricity are treated as direct substiutes (a CES specification with an elasticity of substitution equal to 5, in line with other energy-oriented CGE models [3]). Non-thermal electricity production has a similar structure to the other industrial sectors in the RECU-Water framework (Figure A-4).

In Figure A-2, the technical coefficients $\phi_{Water,sai}$ reflect the water intensities of each SAI within each RESCU-Water region and are adjusted in the dynamic calibration phase (see details below) to account for changes in water effieciency across time, namely:

- For thermal power, changes in cooling technologies from once-through to tower cooling leading to lower withdrawals per unit of output
- Structural changes in industrial water uses as the economy develops and moves towards more water productive activities
- Municipal water efficiency gains of households and services as growth in income per capita allows for the adoption of more water-efficient appliances.

The downstream sectors using water through water distribution networks are differentiated between industrial water-intensive sectors (supplied with water through the industrial water supply sector) and water-flexible users (mainly services and households supplied through the municipal water supply sector – see main text). For industrial sectors, water uses are accounted as the inputs from the industrial water supply sector *iwt* and thus include the cost of treatment and conveyance. These water inputs (water as a commodity) are introduced in the model through a separation between the *iwt* commodity and the non-water commodities (nwc) and a low substitutability specification between the two (Figure A-4).

The model calibration of production functions and final demand is done using the GTAP-9 Power data for 2004 [4] and the elasticities reported in Table A-3. The final demand is represented through household, government and investment as separate accounts. The household demand is implemented in the model through a Linear Expenditure System (LES) to account for subsistence consumption, important especially in developing regions. Government and investment demand functions for commodities are implemented through fixed coefficients (Leontief).

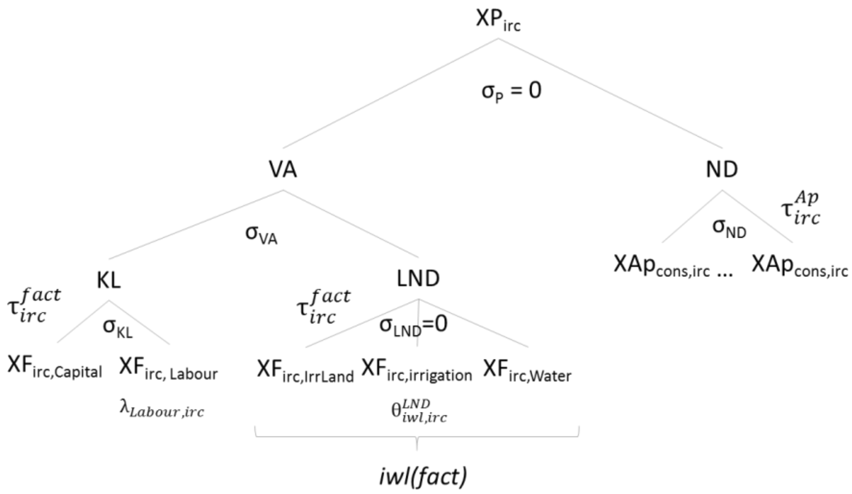


Figure A-1 – Production technology of irrigated crops

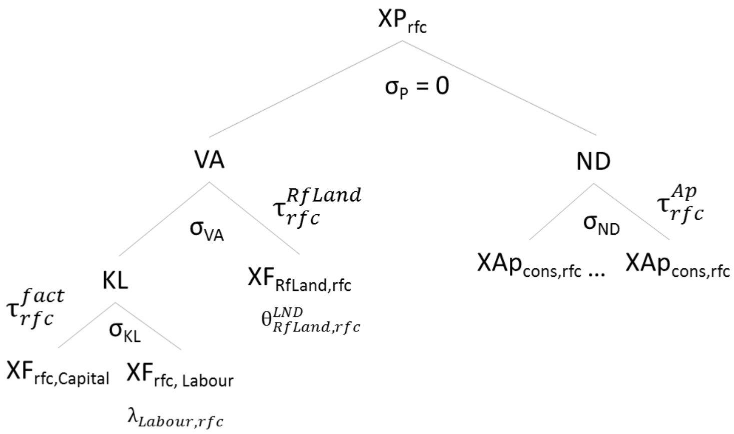


Figure A-2 – Production technology of rainfed crops

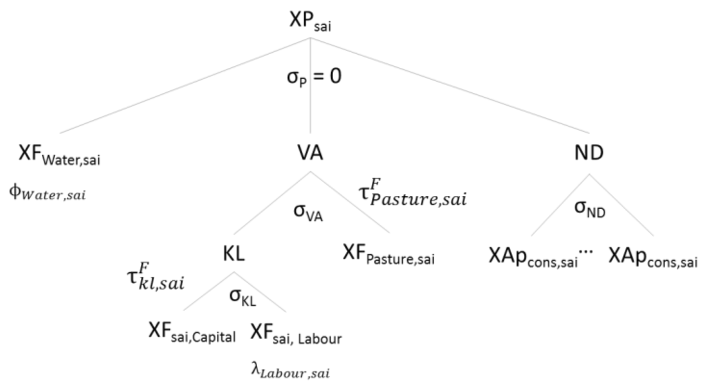


Figure A-3 – Production technology of self-abstracting industries (SAI)

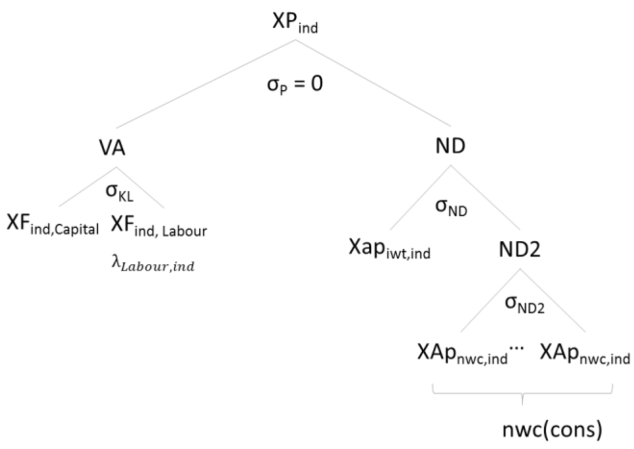


Figure A-4 – Production technology water-intensive industrial sectors (ind)

Table A-3 – Elasticity values in production functions

Elasticity	Value range across sectors	Source
σp top-level	0	GTAP
σ_{VA} top-level VA nest	ESUBVA [0.23-1.68]*	GTAP
σ_{KL} capital-labour nest	ESUBVA [0.23-1.68]*	GTAP
σ_D Armington nest	ESUBD [1.90-5.05]*	GTAP
σ_M inter-regional import substitution	ESUBM [2.60-10.1]*	GTAP
σ_{ND1} for industrial water inputs	0.01	Authors
σ_{ND2} for other inputs	2	Authors

** Dataset values from the GTAP database*

3. Model dynamic calibration

The RESCU-Water model is calibrated across the 2004-2050 time frame to reproduce withdrawal levels under a 'no scarcity' pathway in line with the baseline projections across the five classes of self-abstracting activities - Figure A-5 (see below for the projection calculation procedure). In the 'no scarcity' model baseline, the total regional supply of water in in each year *t* is specified to match the sum of all unconstrained projected sectoral demands $W_{sai,t}$. Therefore, with the calibrated sectoral water intensities, the model generates sectoral water demands equal to $W_{sai,t}$ and sum up to the exogenously specified total water availability at a water market price of zero i.e. no scarcity rents. Considering that the model already determines water withdrawals for irrigation and livestock endogenously (see [1]), the calibration is required only for the other three sectors – thermal electricity *elt*, industrial water supply *iwt* and municipal water supply *mwt*.

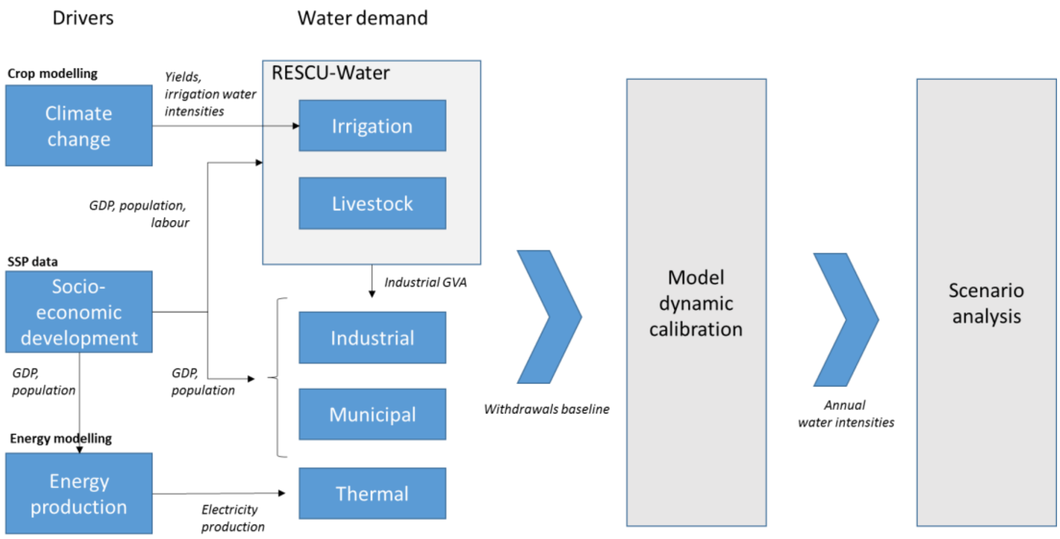


Figure A-5 - Water withdrawals baseline model calibration

$$\phi_{Water,sai,t} = \alpha_{Water}^{sai} \frac{XP_{sai,t}}{W_{sai,t}} \quad (1)$$

$$\alpha_{Water}^{sai} = \frac{W_{sai,2004}}{XP_{sai,2004}} \quad (2)$$

$XP_{sai,t}$ is the sectoral output determined in the model 'no scarcity' baseline where water is not included as a distinct factor of production and in which the constraints of water scarcity are not considered. $W_{sai,t}$ represents the sectoral water withdrawals values as determined in the water demand baseline. The α_{Water}^{sai} is the water share parameter as calculated through the base year model calibration with the $\phi_{Water,sai,t}$ factor productivity equal to 1 (equation (2)).

4. Modelling freshwater scarcity

The modelling of water scarcity in the RESCU-Water model implies a reduction in water availability for economic activities in regions which currently are exceeding or are projected to exceed the levels of long-term sustainable water withdrawals. The introduction of scarcity is thus done by scaling down the water supply FS_{water} in these regions from the unconstrained total demand levels down to a region-specific sustainable withdrawals threshold SWT_r. This supply constraint implies the occurrence of scarcity rents which guide the way freshwater resources are allocated throughout the economy.

The effective introduction of water as a distinct factor of production is done only in water-scarce regions. For these cases, water demand by self-abstracting sectors is endogenised through a specific model demand variable $XF_{Water,sai}$ (equation (3), see Figure A-3) and a water market price variable PF_{Water} (equation (4)). For the 'no scarcity' model base case, total supply of water FS_{water} in each year

t is specified to match the sum of all unconstrained demand levels $W_{sai,t}$. Therefore, with the calibrated $\phi_{Water,sai,t}$ values, the model generates sectoral demands $XF_{Water,sai}$ equal to $W_{sai,t}$ and which sum up to the exogenously specified total supply FS_{water} at a water market price of zero i.e. no scarcity rents.

$$XF_{Water,sai} = \alpha_{Water}^{sai} \frac{XP_{sai}}{\phi_{Water,sai}} \qquad (3)$$

$$PX_{sai} = \alpha_{VA}^{sai} PVA_{sai} + \alpha_{ND}^{sai} PND_{sai} + \frac{\alpha_{Water}^{sai}(1 + \tau_{Water,sai}^{F})PF_{Water}}{\phi_{Water,sai}} \qquad (4)$$

In the other regions, water use calculations are exogenous to the model and are done by multiplying the sectoral output $XP_{sai,t}$ with the α_{Water}^{sai} parameter adjusted for water productivity changes $\phi_{Water,sai,t}$. Through this specification, water inputs are not introduced as independent model variables and thus are not a determinant in production choices, allowing water use to expand or contract given the impacts transmitted from water scarce regions.

While the implementation of the FULL allocation method is inherent to the model specification of all other factors of production as described in [1], the modelling of the other three methods (LIMIT, FRAGM and AGLST) requires changing the water demand functions of the self-abstracting sectors. For the LIMIT method, only a part of the water resources is re-allocable. In the model, this re-allocation is achieved through the introduction of a fraction of resources that is allocated at no cost and in fixed volumes to the different economic activities. Each sector is thus entitled to a $FREE\_WATER_{sai,t}^{r}$ volume calculated for each simulation year t (equation (5)) as a share $free\_alloc$ applied to the unconstrained water demand $W_{sai,t}^{r}$ adjusted by a water demand reduction rate wdr_t^r. The reduction rate wdr_t^r represents the change in total regional water demand required to cap withdrawals at a regional sustainable threshold SWT_r and is calculated annually to reflect changes in the 'no scarcity' baseline withdrawals due to socioeconomic development (equation(6)).

$$FREE\_WATER_{sai,t}^{r} = wdr_t^r * W_{sai,t}^{r} * free\_alloc \qquad (5)$$

$$wdr_t^r = \frac{SWT_r}{\sum_{sai} W_{sai,t}^{r}} \qquad (6)$$

The difference $1\text{-}free\_alloc$ represents the fraction of water resources which can be re-allocated between sectors. Each sector is thus using all its free water as this volume is not influenced by the scarcity price signals, and then adjusts any additional water demand based on its relative water productivity. The cost functions of non-crop self-abstracting industries are specified to account for the partial free allocation of water (equation (7)) by factoring in a water cost share wcs_{sai} reflecting the share of water demand for which the water price PF_{Water} applies (equation (9)). PVA_{sai} and PND_{sai} represent the value of value-added and intermediate goods respectively and which go into the production of self-abstracting industries. For irrigated crops, the Leontief cost function for the land bundle (perfect complementarity of irrigable land, irrigation equipment and water) is implemented through equation (8). Due to the market clearing condition, the sum of demand by all users is equal to the regional water supply $FS_{Water,r}$ set at the sustainable withdrawals thresholds SWT_r (equation(10)).

$$PX_{sai} = \alpha_{VA}^{sai} PVA_{sai} + \alpha_{ND}^{sai} PND_{sai} + \frac{\alpha_{Water}^{sai} wcs_{sai} PF_{Water}}{\phi_{Water,sai}} \tag{7}$$

$$PLND_{irc} = \alpha_{IrrLand}^{LND} \frac{(1+\tau_{IrrLand}^{F})PF_{IrrLand}}{\theta_{IrrLand}^{LND}} + \alpha_{Irrigation}^{LND} \frac{(1+\tau_{Irrigation}^{F})PF_{Irrigation}}{\theta_{Irrigation}^{LND}} + \alpha_{Water}^{LND} \frac{wcs_{irc} PF_{Irrigation}}{\theta_{Water}^{LND}} \tag{8}$$

$$wcs_{sai} = \frac{(XF_{Water,sai} - FREE\_WATER_{sai})}{XF_{Water,sai}} \tag{9}$$

$$FS_{Water,r} = SWT_r \tag{10}$$

The free allocation fraction $free\_alloc$ is set to 0.95 implying that almost all resources are allocated at no cost. This determines only the remaining 5% of the sustainable water supply to be shifted from one activity to another and results in a reduction of all water uses almost proportional to that of total water withdrawals.

For the FRAGM allocation method, the exogenous supply of water is separated into two independent supply variables – $FSWA_r$ for crops and $FSWI_r$ for non-crops. The market clearing condition for water endowments is thus specified distinctly for the two supply types (equations (11) and (12)).The exogenous levels of *FSWA* and *FSWI* are set such that the reduction from unconstrained withdrawals for each of two water user groups is proportional to the overall required reduction to meet the regional sustainability threshold.

$$FSWA_r = \sum_{crops} XF_{Water,crops,r} \tag{11}$$

$$FSWI_r = \sum_{non-crops} XF_{Water,non-crops,r} \tag{12}$$

The AGLST allocation method is enabled by specifying water as a production factor only to irrigated crops. The use of water by non-crop self-abstracting sectors $EXF_{Water,sai}$ is proportional to the output of these sectors by using the sector specific water intensities and the calibrated water productivities $\phi_{Water,sai,t}$ (equation (13)). Thus, scarcity rents PF_{Water} are not included in the cost function of these sectors and therefore do not influence water demand in these activities. To determine water availability for irrigation, the $EXF_{Water,sai}$ volumes are deducted from the sustainable thresholds SWT_r (equation (14)) to determine total water supply applicable only to irrigated crops (equation (15)).

$$EXF_{Water,sai} = \frac{\alpha_{Water}^{sai} XP_{sai}}{\phi_{Water,sai}} \tag{13}$$

$$FS_{Water,r} = SWT_r - \sum_{sai} EXF_{Water,sai,r} \tag{14}$$

$$FS_{Water,r} = \sum_{irc} XF_{Water,irc,r} \tag{15}$$

5. Baseline water demand calculation for 2004-2050

By using 2004 levels obtained through the water accounting data from EXIOBASE [5], an unconstrained 'no scarcity' demand is projected across the five self-abstracting sectors – irrigated crops, livestock, thermal power production, industrial supply and municipal supply. This structure is similar to that found in the other studies focusing on the relationship between future freshwater demand and socio-economic development [6]–[9].

5.1. Irrigation and livestock water demand

Water demand projections obtained endogenously are calculated through the use of a "no scarcity" model baseline for the SSP2 pathway. As described in [1] socio-economic development is integrated into RESCU-Water by taking into account exogenous GDP growth rates, changes in population, and changes in labour and capital supply. The 'no scarcity' world implies that any present or future water deficit does not have an impact on production and consumption decisions. In this run, instead of treating water endowments as a factor of production with a corresponding market price, water withdrawals are attached to the use of the irrigation facility as done in [1] for irrigation water, and directly to sectoral output for livestock. The "bottom-up" representation of the crop sectors in the RESCU-Water framework facilitates the calculation of water demand for irrigation. Irrigation water requirements are thus determined by changes in crop demand coming from income and population growth.

5.2. Industrial and municipal water demand

Projections of industrial and municipal water use are undertaken outside the model framework and build on the work conducted previously in water scarcity assessments. The evolution of each of the two categories is thus determined separately and is explained by changes in scale, structure and efficiency in water use. The relationship between industrial water demand and economic activity is established similarly to the PCR-GLOBWB model [10] as a product of the scale of economic activity, economic development (ED) and technological change (TC) (16). Industrial activity is calculated as the root square of changes in industrial gross value added (GVA^{ind}), specifying a slow-down of in the expansion of industrial water demand with industrial output. Next, the ED component captures the changes in the structure of industrial activity as a function of per capita *GDP* and per capita energy demand *EN* (17). Last, the TC component reflects the tendency of technologies to become more water efficient over time. In line with the approach in [11], TC values distinguish between four types of regions depending on their hydrological and economic development profile. The GVA values used are determined by RESCU-Water through the 'no scarcity' baseline as an aggregated value for industrial sectors. The energy demand values are calculated through the TIAM-UCL model [12] for SSP2 and are consistent with the power production projections used for the thermal cooling water calculations explained below.

$$IWD_t^r = IWD_{2004}^r * \frac{GVA_{r,t}^{ind}}{GVA_{r,2004}^{ind}}^{0.5} * ED_t^r * TC_t^r \quad (16)$$

$$ED_t^r = AVERAGE\ (\frac{GDP_{r,t}^{pc}}{GDP_{r,2004}^{pc}}^{0.5}, \frac{EN_{r,t}^{pc}}{EN_{r,2004}^{pc}}^{0.5}) \quad (17)$$

Municipal water demand (MWD) is determined similarly to industrial water (equation (18)). The MWD scale driver is the regional population, whilst changes in the structure of water use and water efficiency gains are captured through the same ED and TC parameters respectively, similarly to the industrial water demand.

$$MWD_t^r = MWD_{2004}^r * \frac{P_t}{P_{2004}} * ED_t^r * TC_t^r \quad (18)$$

Table A-4 - Technological change in industrial and municipal water use (gains per annum)

	HD	**HI**	**LD**	**LI**
Industrial	0.6%	1%	1%	1.1%
Municipal	0.3%	0.5%	0.5%	0.65%
Regions	China, Central Asia, Southeast Asia, North and South Latin America, Eurasia, Brazil, Central Africa, Sahel	Northern Europe, USA, Northeast Asia	India, South Asia, Northern Africa, Southern Africa	Middle East, Southern Europe, Australia&NZ

HD = water abundant developing, HI = water abundant industrialised, LD = water-scarce developing, LI = water scarce industrialised

The values for water efficiency improvements through technological change are presented in Table A-4. The industrial values are those used in the model inter-comparison work in [11] for SSP2. The municipal values are, however, adjusted to fit the projections of municipal water demand from other studies.

5.3. Thermoelectric cooling water demand

The specification of water use for thermal power plant cooling is essential as due to its weight in overall water abstraction, amounting to combined volumes of the global industrial and municipal water uses. The dynamics in withdrawals for this use type are tied to electricity production coming from combustion plants. However, the relationship is not linear due to the changing nature of the thermoelectric generation mix and the large differences in water intensities between cooling technologies.

The baseline for cooling water demand is thus calculated bottom-up outside the RESCU-Water framework based on 'business-as-usual' electricity projections (no climate change policy) obtained from the TIAM-UCL energy systems model for SSP2. This calculation is completed in several steps (Figure A-6) by taking into account changes both in the power production technological mix but also the possible evolution of cooling technologies towards more water-efficient options.

TIAM-UCL is a global linear optimisation model of the global energy system based on the TIMES modelling platform [13]. Energy production is determined for 16 world regions and is represented through a technology-rich bottom-up approach. The objective function of the partial equilibrium model is the minimisation of total discounted system costs at given exogenous production costs. The model is solved in 5-year time steps in the 2005-2100 time horizon and is primarily used to determine de-carbonisation pathways for different GHG concentration targets.

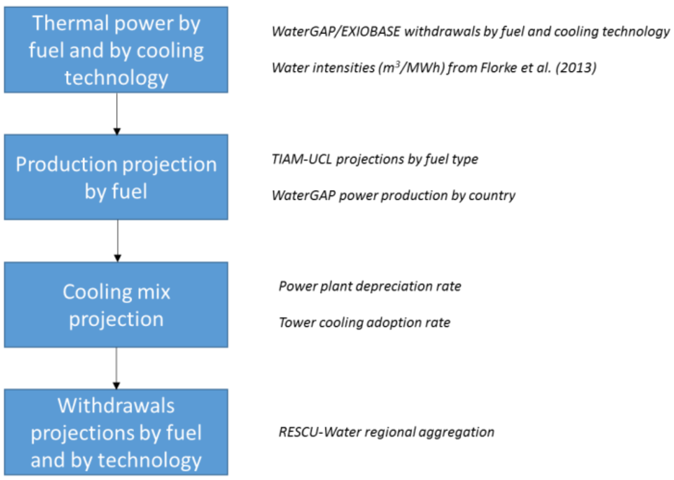


Figure A-6 - Workflow for projecting thermal cooling water demand

In a first step, thermal power electricity generation by fuel and by cooling type is derived from the WaterGAP data published through EXIOBASE. The dataset comprises global water uses for 2007 reported across the two main cooling methods (once-through and tower cooling) and structured around 44 world regions. The relevance of the WaterGAP data consists of the selection of power plants based on their location such that only freshwater withdrawals for cooling are considered thus excluding coastline power generation. The translation of withdrawal values into electricity production value is done using the water intensities measured in m^3/MWh (Table A-5) employed initially in [6] to determine thermal cooling withdrawals.

Table A-5 - Power plant water intensities by cooling method (m^3/MWh)

Fuel	**Once-through**	**Tower (closed-loop)**
Coal	132.5	2.1
Nuclear	160.85	1.5
Gas (combined cycle)	52.05	0.4

Data source: [6]

In the second step, EXIOBASE/WaterGAP regional production values are downscaled to a country level by using disaggregated production statistics for the base year. Production by fuel type is then projected using growth rates[1] obtained from TIAM-UCL for a business-as-usual climate policy assumption using SSP2 GDP and population dynamics. As the regional aggregation in TIAM-UCL is different from that in EXIOBASE, each country inherits the production dynamics of its TIAM region and the initial regional cooling mix of its EXIOBASE region.

The cooling mix evolution is then determined in the third step. This calculation is done by taking into account that newer power plants are likely to become more water efficient through a gradual adoption of tower-cooling. For each year, power generation by fuel and by cooling type is split into two vintages. The “old” vintage represents the production capacity inherited from the previous year depreciated with a 2.5% rate (40-year lifetime assumption for power plants) and for which the cooling mix is fixed. The “new” vintage is the additional capacity required to generate electricity up to the annual projected levels. The new vintage uses a *tower/once-through cooling ratio* updated annually in which the weight of tower cooling progresses by 2%.

In the fourth step, production values by fuel and by cooling method combined with the water intensities in Table A-5 enable the calculation of withdrawals along the two dimensions in the 2004-2050 time horizon. Withdrawals are thus affected both by changes in production technologies with some fuels being more efficient than others (e.g. gas versus coal) and by changes in the cooling mix with a tendency towards the use of more water-efficient methods. Finally, as the RESCU-Water model combines all thermal production technologies into one sector, all country-level cooling withdrawals are summed up and aggregated to the RESCU-Water regional structure

[1] Negative growth rates are used to calculate pre-2007 production values

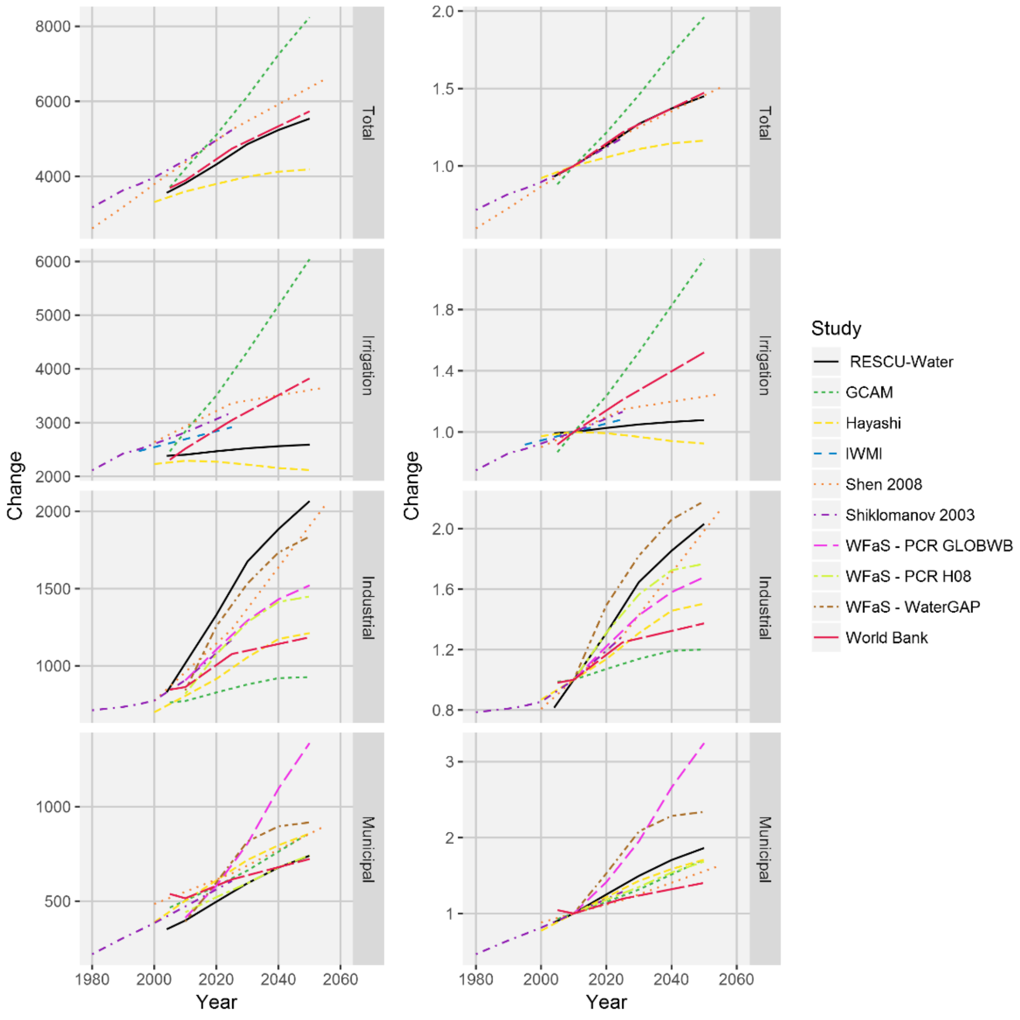
6. Baseline 'no scarcity' withdrawals

6.1. Global withdrawals

In the RESCU-Water baseline, global withdrawals in 2050 grow by 55% compared to the base year 2004 to reach 5539km^3. As obtained previously for SSP2, irrigation water demand grows by only 9%, whereas other uses have a more pronounced expansion – industrial (436%), municipal (249%), thermal cooling (67%), livestock (37%).

These RESCU-Water total withdrawal values are comparable to other global projections. Figure A-7A shows the global withdrawals expressed in absolute terms obtained across a number of modelling efforts. As base years and withdrawal reference values differ from one study to another, to capture the scale in the expansion of water demand, relative changes[2] are also included in Figure A-7B. It should be noted, that the structure of withdrawals varies across studies, whilst only a subset of the projections covers all water withdrawals with some focusing on some specific uses, e.g. industrial an municipal water in Wada et al. (2016).

[2] The year 2010 was chosen as reference to allow comparison with the WFaS work in Wada et al. (2016) which only report data starting with this year



A) Absolute values (km^3) B) Changes from 2010 levels

Figure A-7 - Baseline withdrawals compared to other studies

Studies: RESCU-Water (this study), GCAM [14]*, Hayashi* [15]*, IWMI* [16]*, Shen 2008* [17]*, Shiklomanov 2003* [18]*, WFaS PCR GLOBWB, H08, WaterGAP in* [11]*, World Bank* [19]

Irrigation withdrawals for the RESCU-Water baseline are found at the lower end of projections. Industrial withdrawals (reported Figure A-7B as the sum of industrial supply and thermal cooling for comparative reasons[3]) are on the higher end of the projected values. Interestingly, the lowest growth and the highest growth are obtained in GCAM and WaterGAP which both separate manufacturing and thermal cooling withdrawal dynamics, with changes for RESCU-Water being more in line with those obtained in WaterGAP. For municipal water demand, the baseline values are similar to the more central estimates.

[3] Only GCAM reports projections for thermal cooling withdrawals; WaterGAP values for thermal and manufacturing withdrawals are bundled as industrial uses in Wada et al. (2016)

6.2. Regional withdrawals

Regions expanding most their total water demand are those with a high increase in GDP and population. Therefore, baseline withdrawals for 2004-2050 see a considerable growth in most developing regions (The results obtained for each RESCU-Water region cannot be thoroughly compared to other studies. Other projections are generally reported as global aggregates, with only the WFaS model inter-comparison work in [11] presenting results for a sample of eight countries of which only four are distinctly accounted for in RESCU-Water. In the 2010-2050 period, industrial withdrawals for China grow five times in WaterGAP and six times in PCR-GLOBWB, whereas H08 reports an increase of only 30% and also comprises a decline post-2030. The corresponding values in RESCU-Water lead to a sixfold increase, comparable thus to PCR-GLOBWB. For municipal water, the expansion patterns across the three WFaS models are similar to that of industrial uses. Hence RESCU-Water values are lower than WaterGAP and PCR-GLOBWB but higher than H08. The agreement of the RESCU-Water baseline with the WFaS models output is lower for the industrialised regions. WaterGAP and H08 report a marked decrease in the USA for industrial water demand, whilst the RESCU-Water projections increase slightly by 5%. The USA municipal water demand increases significantly in H08 and PCR-GLOBWB, similarly to RESCU-Water, but less so in WaterGAP.

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6). Also, as demand in non-agricultural uses expands at high rates, irrigation withdrawals generally fall in importance, although maintaining an important role in most cases – see

Figure A-8.

Table A-6 - Regional withdrawals in 2004 and 2050 relative to TRWR

RESCU-Water region	Total withdrawals (km³)		Change	% TRWR	
	2004	2050		2004	2050
India	662.9	1,050.8	59%	35.0%	55.4%
China	511.5	985.3	93%	17.7%	34.0%
USA	451.6	526.8	17%	21.6%	25.2%
Middle East	402.3	569.8	42%	97.6%	138.2%
South Asia	316.2	331.8	5%	109.0%	114.4%
Southeast Asia	276.2	395.6	43%	4.1%	5.8%
Northern Africa	172.2	201.9	17%	79.6%	93.3%
Southern Europe	158.8	166.3	5%	17.1%	17.9%
North Latin Am	137.6	247.9	80%	7.4%	13.2%
Central Asia	88.9	143.7	62%	20.1%	32.4%
Northern Europe	88.0	186.7	112%	6.8%	14.4%
Eurasia	79.7	181.8	128%	1.7%	3.9%
Northeast Asia	56.2	52.9	-6%	10.0%	9.4%
Canada	40.3	26.3	-35%	1.4%	0.9%
South Latin Am	37.4	105.8	183%	2.0%	5.7%
Brazil	27.8	51.5	85%	0.3%	0.6%
Australia &NZ	25.8	32.8	27%	3.2%	4.0%
Central Africa	23.7	49.9	110%	0.9%	1.9%
Southern Africa	17.6	25.2	43%	8.6%	12.3%
Sahel	9.3	13.6	47%	0.9%	1.3%

Total water demand in China is largely driven by a ten-fold increase in industrial water requirements and a doubling of municipal and thermal cooling water demands. Central Africa has a more balanced growth with municipal and industrial demand playing equal parts. Thermal cooling demand doubles, however, remains at insignificant levels in the region. Demand in Brazil is also determined by an important growth across all non-agricultural users.

For the industrialised regions, the sign of change varies from one case to another. The USA sees an expansion of withdrawals by 17% mainly driven by municipal withdrawals. Australia&NZ face a similar dynamic leading to an increase of 27% in total withdrawals. The expansion in cooling water determines a significant growth in total demand in Northern Europe, as the TIAM-UCL 'business-as-usual' scenario for power production relies largely on thermoelectric generation. In contrast, the reduction in withdrawals in Canada is driven by a decrease in thermal cooling withdrawals.

The baseline water demand indicates that regions which are already water-stressed continue to increase their reliance on unsustainable water withdrawals. Regions with base year withdrawal levels close to or even above the TRWR (Middle East and South Asia) further expand the pressure over their aquifers. Northern Africa is also approaching the upper limit of renewable water availability by 2050.

The results obtained for each RESCU-Water region cannot be thoroughly compared to other studies. Other projections are generally reported as global aggregates, with only the WFaS model inter-comparison work in [11] presenting results for a sample of eight countries of which only four are distinctly accounted for in RESCU-Water. In the 2010-2050 period, industrial withdrawals for China[4] grow five times in WaterGAP and six times in PCR-GLOBWB, whereas H08 reports an increase of only 30% and also comprises a decline post-2030. The corresponding values in RESCU-Water lead to a sixfold increase, comparable thus to PCR-GLOBWB. For municipal water, the expansion patterns across the three WFaS models are similar to that of industrial uses. Hence RESCU-Water values are lower than WaterGAP and PCR-GLOBWB but higher than H08. The agreement of the RESCU-Water baseline with the WFaS models output is lower for the industrialised regions. WaterGAP and H08 report a marked decrease in the USA for industrial water demand, whilst the RESCU-Water projections increase slightly by 5%. The USA municipal water demand increases significantly in H08 and PCR-GLOBWB, similarly to RESCU-Water, but less so in WaterGAP.

[4] Again, industrial withdrawals in [11] include thermal cooling values. The comparison with RESCU-Water is made accordingly.

Figure A-8 - Regional withdrawals 2004 and 2050 by use category (in km3)

6.3. Thermal cooling withdrawals

Thermoelectric production using freshwater for cooling purposes grows across all regions except Canada. Globally production grows by 141% in the 2004-2050 period with the highest increases occurring in China, Northern Europe, India, USA and Eurasia (Figure A-9B). Global freshwater withdrawals required for these production levels increase by only 67% due to the transition towards a more water-efficient cooling methods mix.

Tower cooling thus expands withdrawals by 182% compared to 64% for once-through. Nevertheless, given the significant difference in water withdrawal intensities between the two cooling methods, freshwater volume for once-through cooling are still dominant (Figure A-9C) despite the growth in electricity output coming mainly from tower-cooled power plants (Figure A-9D).

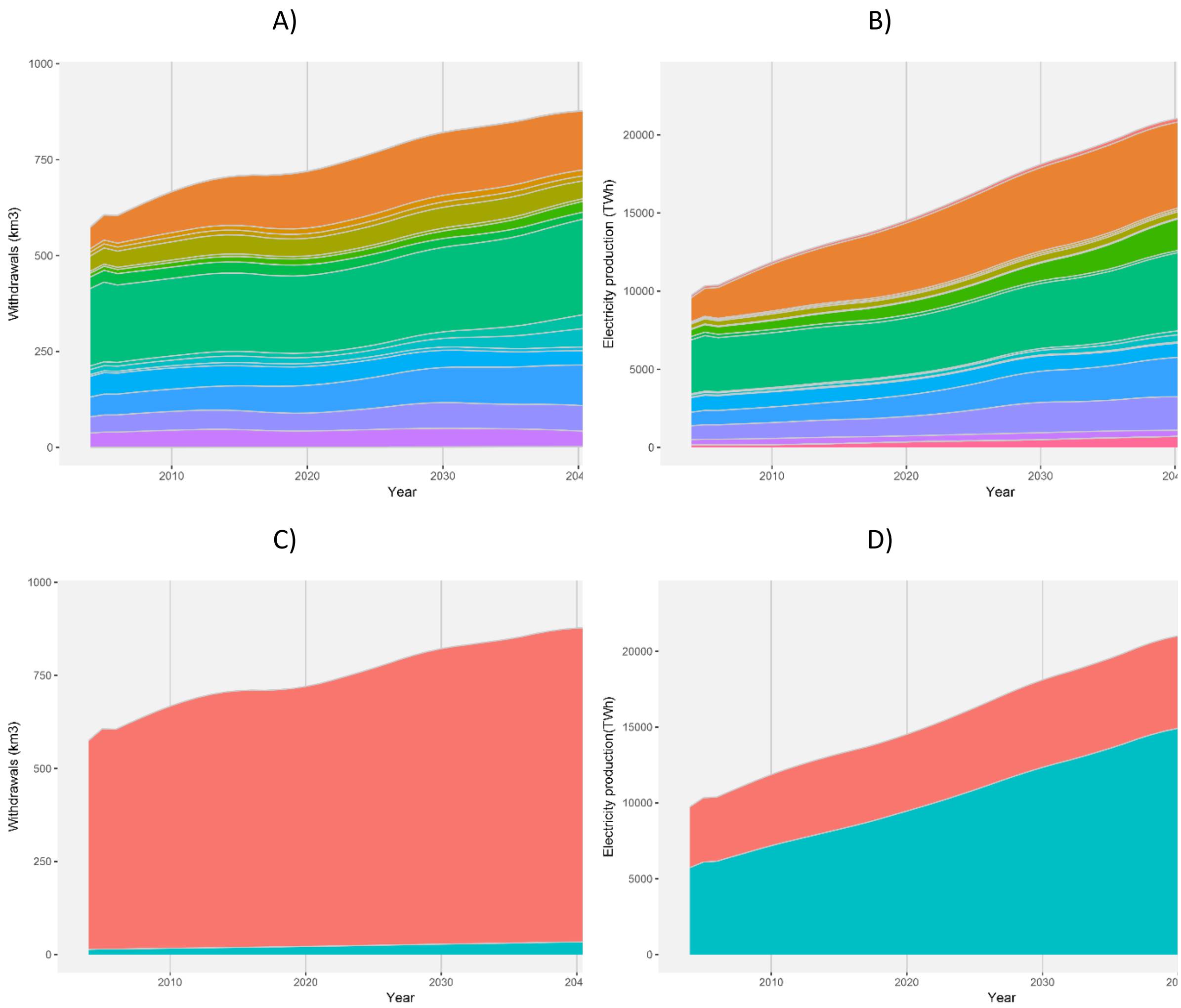


Figure A-9 - Thermal withdrawals and electricity production by region and by cooling method

7. Sustainable withdrawals thresholds

Thresholds for sustainable withdrawals are set for regions which are already either using a large share of their renewable resources or are experiencing recurring groundwater depletion. Middle East, Northern Africa and South Asia qualify through both criteria, whereas India experiences river basin overexploitation in many areas [20], [21] indicating that a further expansion of water withdrawals under current spatial patterns of crop production would lead to an exacerbation of this issue and would pose a long-term threat to groundwater availability across vast geographical areas.

In light of this regional heterogeneity, a few sustainability thresholds can be considered – TRWR[5], TRWR with environmental flows requirements deducted, and 40% of TRWR as a marker for severe water stress following the thresholds set in [6]. The first is an absolute withdrawal limit given by renewable water availability measured through TRWR. Regions going over this value are certain to have a generalised aquifer over-exploitation. The second standard includes provisions for the environmental flow requirements (EFR) which in Figure A-10 are considered to be 20% of TRWR as the lower bound for the estimations in [22]. The third threshold also accounts for the intra-annual accessibility of freshwater resources and the risk of impairment of environmental requirements and downstream users within a river basin.

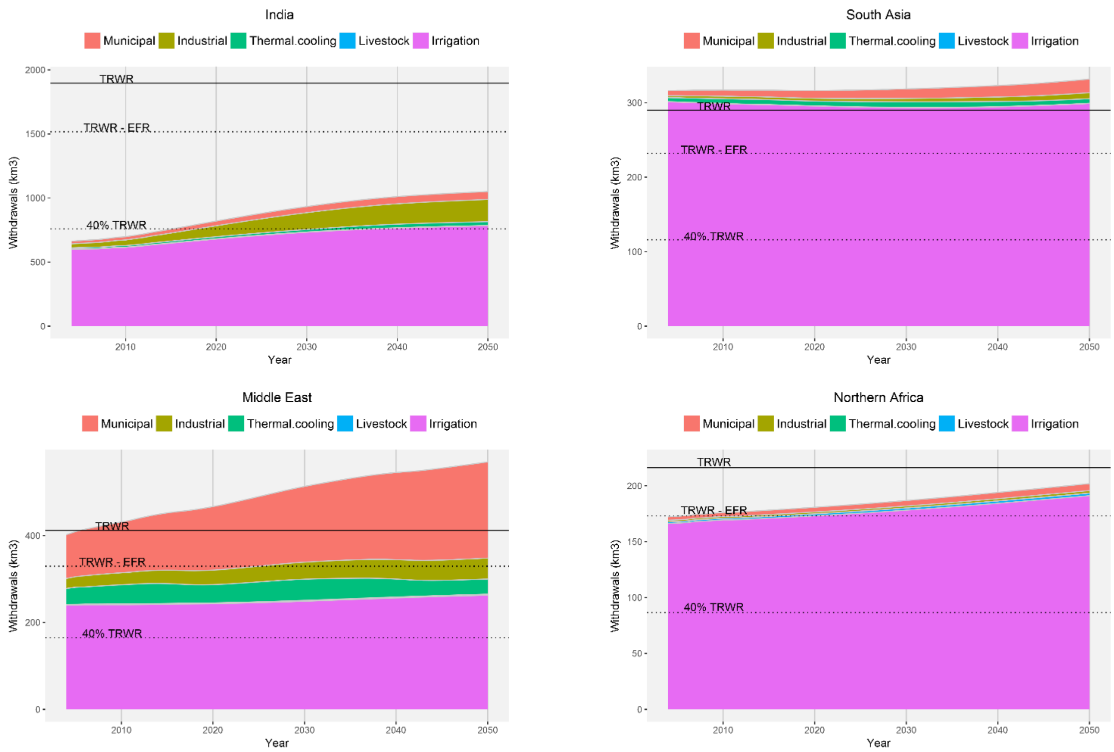


Figure A-10 - Baseline withdrawals in regions with water deficits – SSP2

[5] Total Renewable Water Resources, determined as the sum of total internal resources and the inflow from neighbouring regions

For each region a different sustainability level is set – India 40% of TRWR to prevent a significant further amplification of groundwater depletion[6], South Asia and Northern Africa 80% of TRWR (TRWR minus EFR), Middle East 100% of TRWR. The choice of 100% TRWR threshold for the Middle East comes from the infeasibility in finding a model solution with an 80% threshold in the agriculture-last (AGLST) allocation method given the relative size of baseline water use for irrigation and the required reduction in withdrawals at 80% of TRWR.

8. Additional model results

8.1. Output and water withdrawal changes in crop sectors

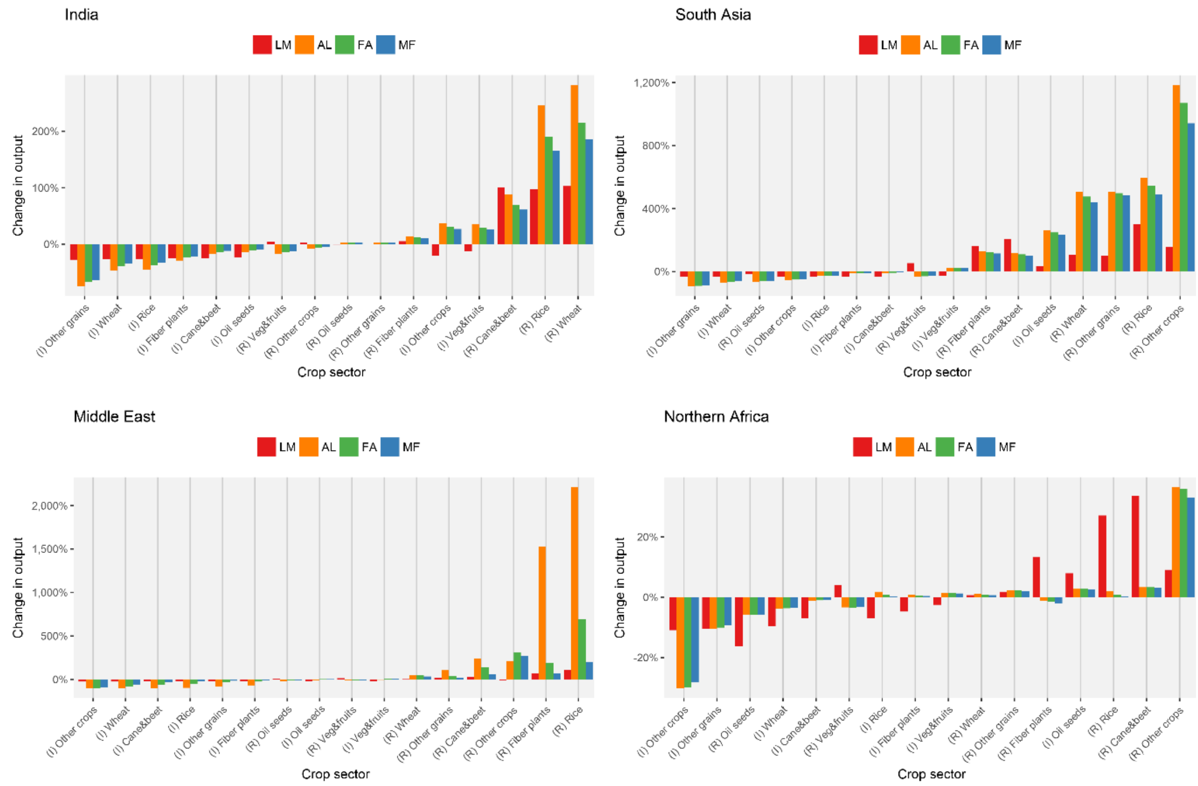


Figure A-11 - Crop production impacts by growing method – values in 2050

Note: (I) – irrigated, (R) – rainfed

[6] This threshold, being higher than 2004 levels, also assumes that withdrawals can still be expanded in river basins which are not currently over-exploited.

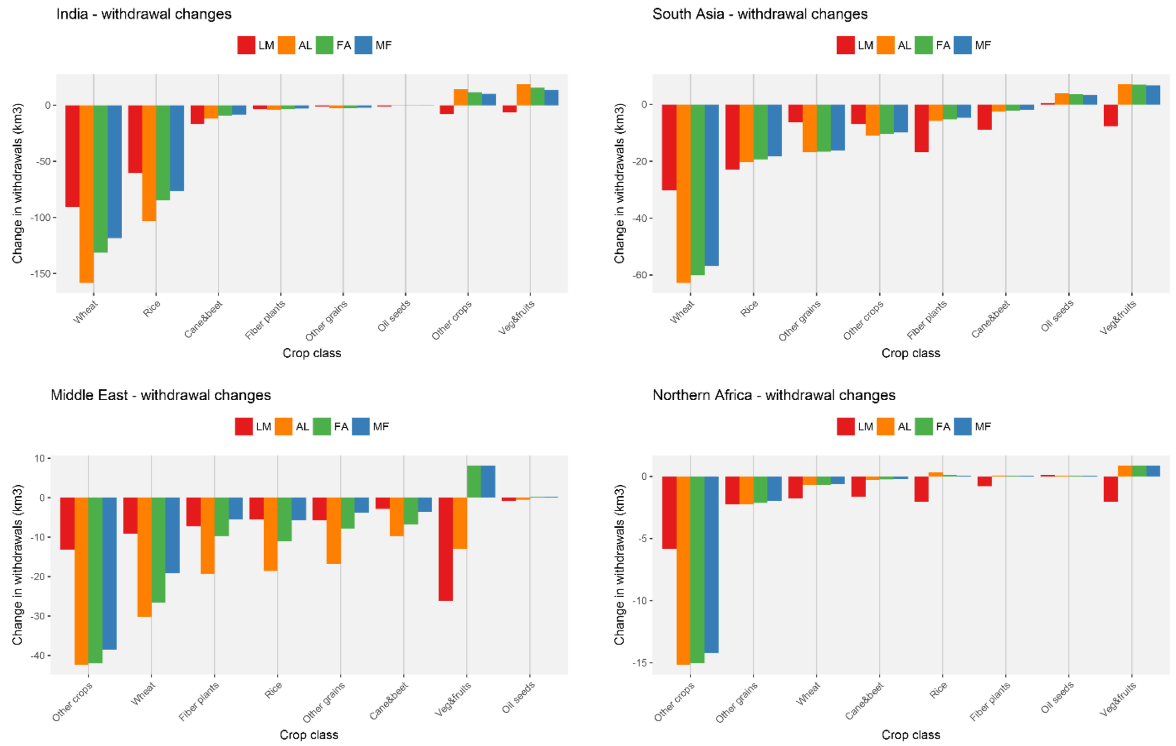


Figure A-12 - Withdrawal changes by irrigated crop type in 2050 (in km³)

8.2. International trade

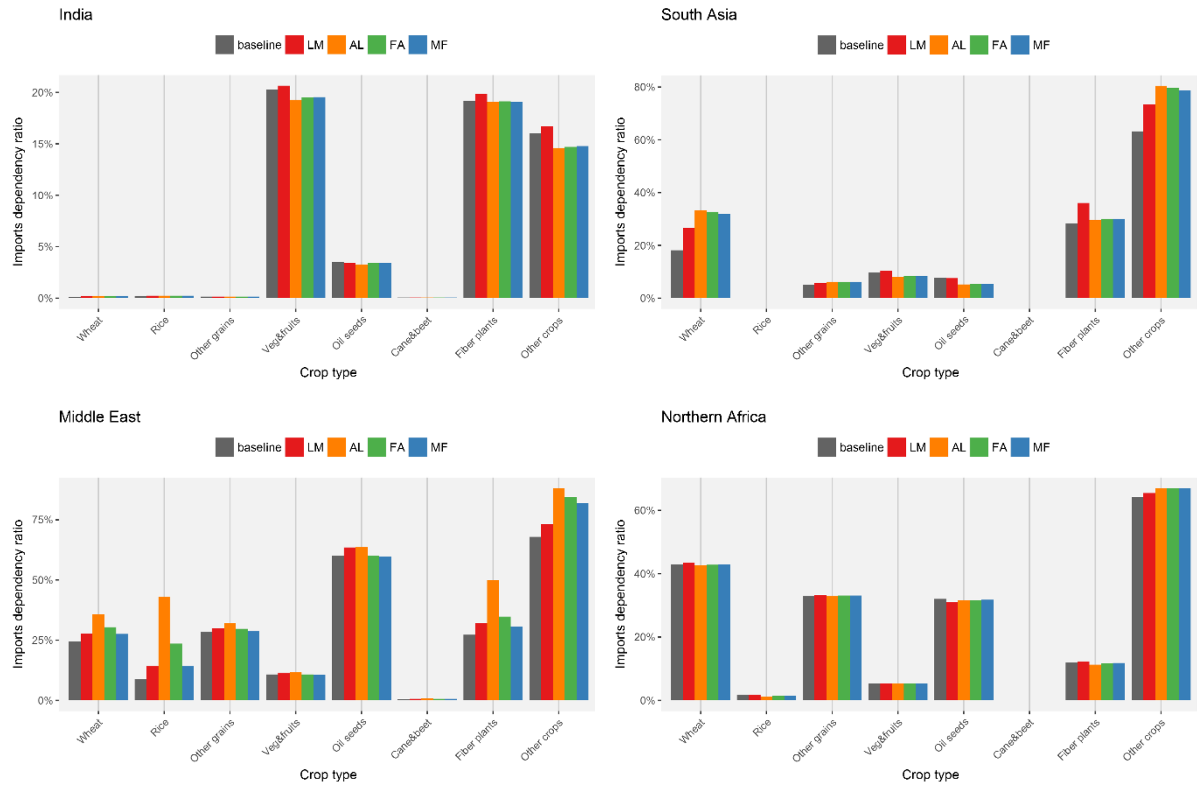
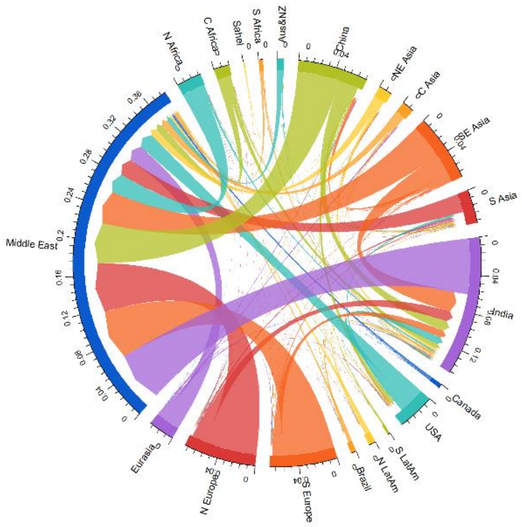
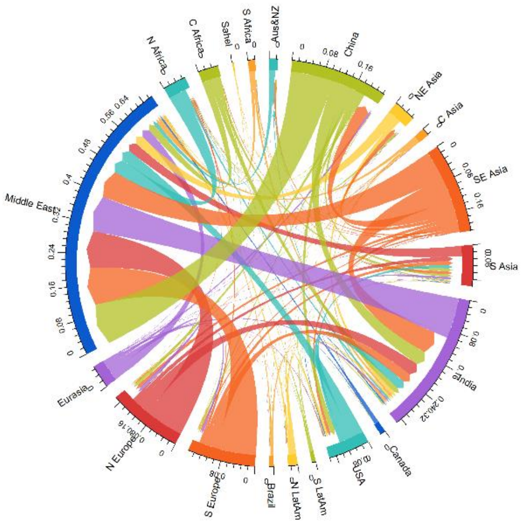


Figure A-13 - Crop imports dependency ratio by region – values for 2050

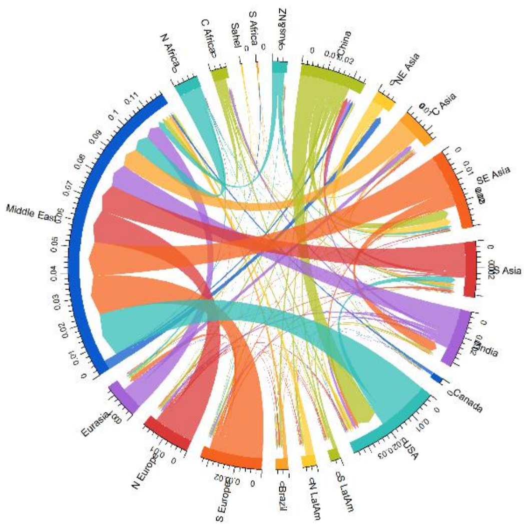
FA

LM





AL FM



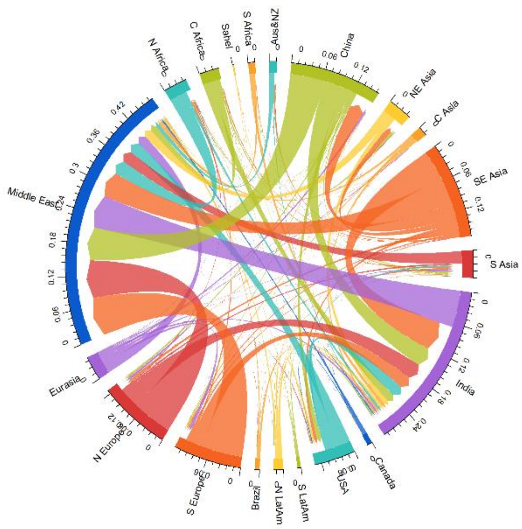


Figure A-14 - Virtual water trade of industrial water by allocation method (in km³)

FA LM

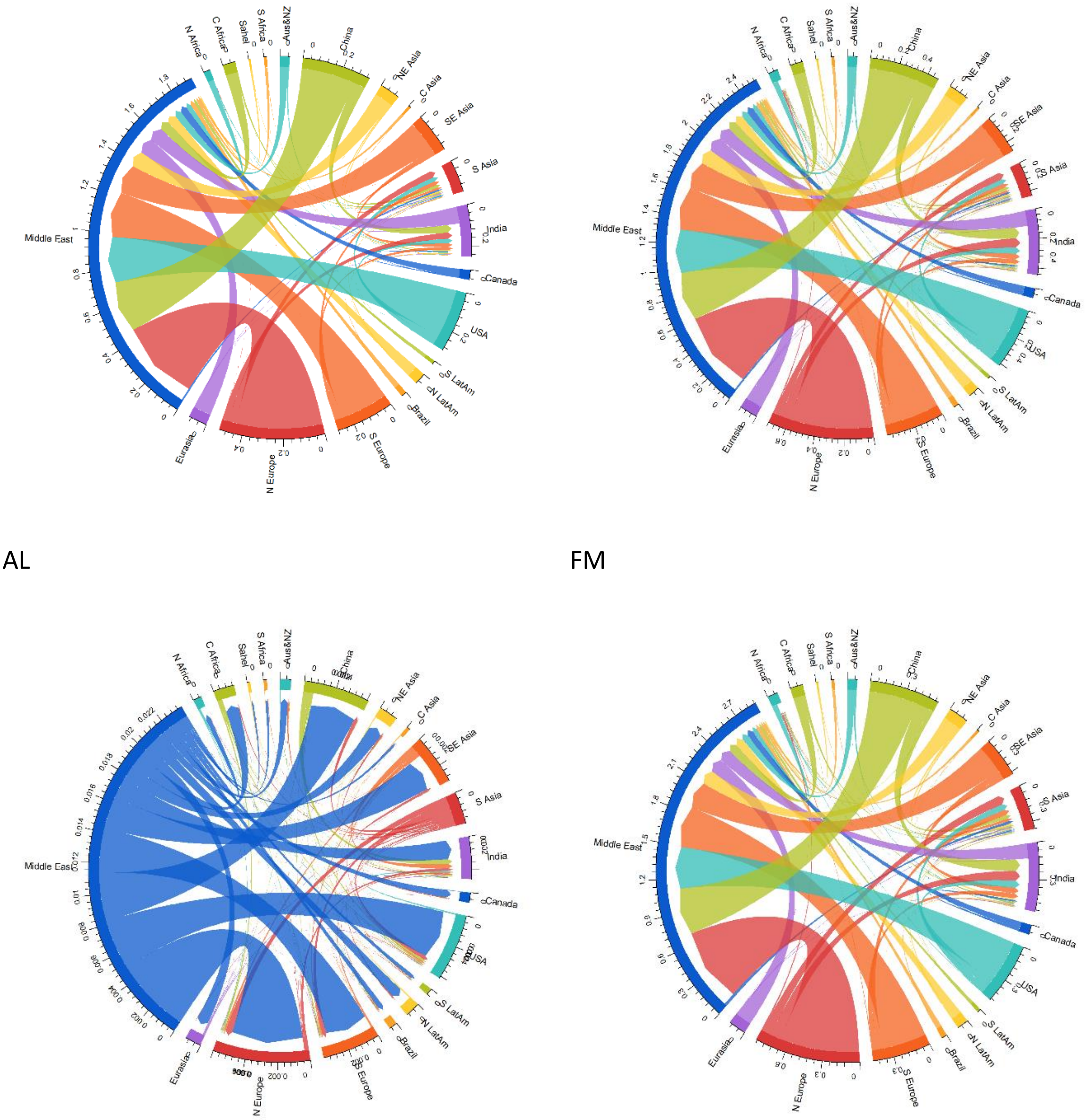


Figure A-15 - Virtual water trade of municipal water by allocation method (in km³)

9. Sensitivity analysis of water inputs substitutability in industrial sectors

This sensitivity analysis was conducted to test the robustness of the model results in relation to the elasticity of substitution σ_{ND2} between industrial water inputs and the composite of all other intermediate inputs ND (see Figure A-4). This was done by increasing the value of σ_{ND2} from the initial level of 0.01 (close to perfect complements) to a level of 2 for the LM allocation method (the variant with the highest GDP impacts of water scarcity).

The negative impacts over real GDP are considerably reduced across all regions (Table A-7). In India these even become positive for an elasticity value of over 0.5 marking the re-allocation of non-water resources to non-crop sectors boosting their output (Figure A-16). For South Asia and the Middle East however, the impacts are still non-negligible even for the highest elasticity value.

The reduction in impacts with an increased elasticity value is observed across all sectors (Figure A-17), but notably for the water-intensive sectors using industrial water as an input (primary energy, chemicals, manufacturing, mining and paper). The substitution effect is felt also for thermal power generation as more water is diverted from the industrial water sector to the other self-supplied sectors – this is in spite of self-abstracting sectors having a zero-elasticity of substitution of water as a factor of production.

Table A-7 - Real GDP impacts in RESCU-Water regions by sigmaND2 value - Limited Mobility (LM) allocation method (values in percentage points)

Region	0.01	0.05	0.1	0.5	2
Middle East	-1.797	-1.599	-1.480	-1.292	-1.232
South Asia	-1.606	-1.332	-1.131	-0.835	-0.770
India	-0.435	-0.148	-0.057	0.042	0.071
Northern Africa	-0.022	-0.017	-0.014	-0.009	-0.006
Central Asia	-0.016	-0.013	-0.012	-0.009	-0.009
Eurasia	-0.009	-0.007	-0.005	-0.003	-0.003
China	-0.002	-0.002	-0.002	-0.001	0.002
Northern Europe	-0.002	-0.001	-0.001	-0.000	-0.000
Southern Europe	-0.001	-0.000	-0.000	0.000	-0.000
Northeast Asia	-0.000	-0.000	-0.000	-0.000	-0.001
North Latin Am	-0.001	-0.000	-0.000	0.000	0.000
USA	0.000	0.000	0.000	0.001	0.000
Southeast Asia	-0.002	0.001	0.002	0.003	0.001
Canada	0.000	0.001	0.001	0.001	0.001
Central Africa	-0.006	-0.000	0.002	0.006	0.007
Australia&NZ	0.001	0.002	0.003	0.004	0.003
Brazil	0.002	0.002	0.002	0.003	0.003
Sahel	0.001	0.004	0.005	0.006	0.004
Southern Africa	0.001	0.004	0.005	0.006	0.005
South Latin Am	0.005	0.006	0.006	0.006	0.005
World	**-0.146**	**-0.109**	**-0.093**	**-0.072**	**-0.066**

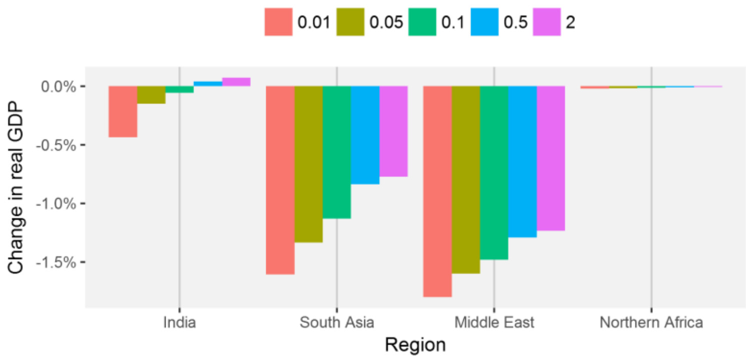


Figure A-16 - Real GDP impacts in water-scarce countries by σ_{ND2} value - LM allocation method

Note: the 0.01 value is the base value used in the model runs reported in the Results section

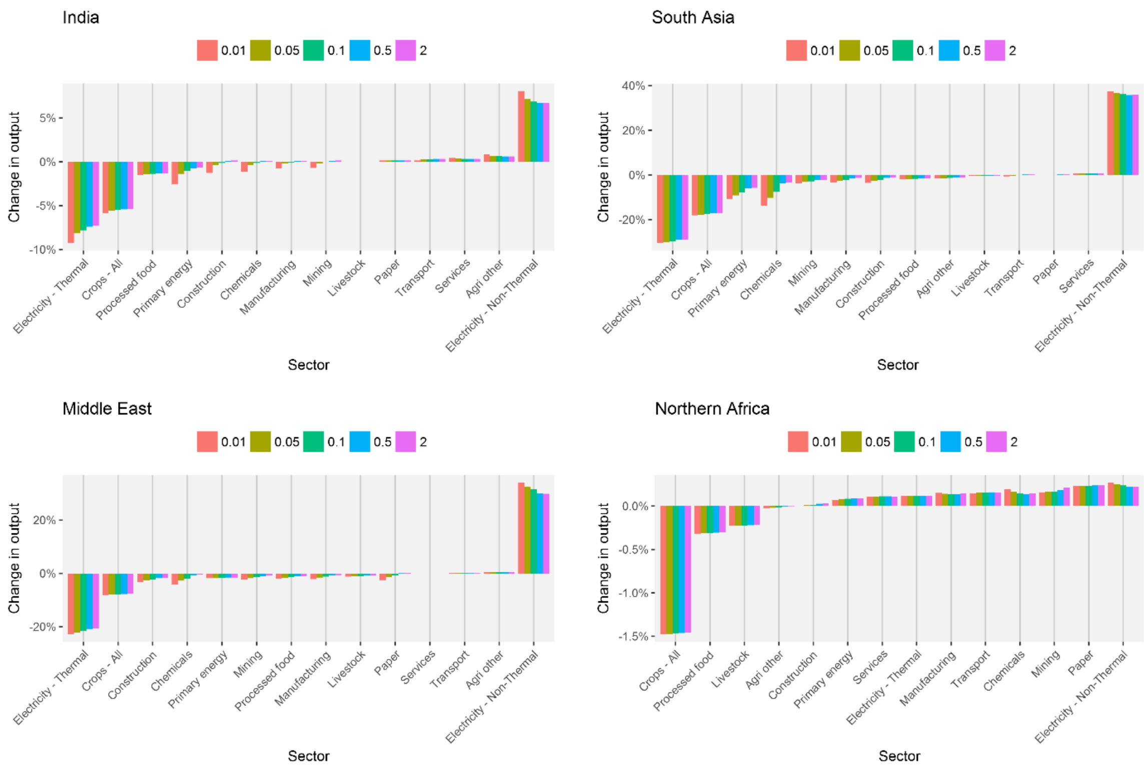


Figure A-17 - Sectoral output impacts in water scarce regions by sigmaND2 value - Limited Mobility (LM) allocation method

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