Global economic and food security impacts of demand-driven water scarcity

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Abstract

Global freshwater demand will likely continue its expansion under current expectations of economic and population growth. Withdrawals in regions which are already water-scarce will impose further pressure on the renewable water resource base threatening the long-term availability of freshwater across the many economic activities dependent on this resource for various functions. This paper assesses the economy-wide implications of demand-driven water scarcity under the "middle-of-the-road" SSP2 pathway by considering the trade-offs between the macroeconomic and food security impacts. The study employs the RESCU-Water CGE model comprising an advanced level of detail regarding water uses across economic activities and which allows for a sector-specific endogenous adaptation to water scarcity. A sustainable withdrawal threshold is imposed in regions with extended river-basin overexploitation (India, South Asia, Middle East and Northern Africa) whilst different water management options are considered through four alternative allocation methods across users. The scale of macroeconomic effects is dependent on the relative size of sectors with low-water productivity, the size of water uses in these sectors, and the flexibility of important water users to substitute away from water inputs in conditions of scarcity. The largest negative GDP deviations are obtained in scenarios with limited mobility to re-allocate water across users. A significant alleviation is obtained when demand patterns are shifted based on differences in water productivity, however, with a significant imposition on food security prospects.

Key words: Computable General Equilibrium, Freshwater withdrawals, Water scarcity, Food security, Economy-wide impacts, Virtual water

JEL Classification: D58, Q15, Q17, Q18, Q25, Q56

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1. Introduction

As most countries aspire to continued economic development, water demand may also sustain the upward trend in human withdrawals observed in the past century. Thus far irrigation has been the most important driver in the expansion of global freshwater withdrawals. Nevertheless, other sectors have also played a significant role, notably in industrialised countries, e.g. water for power plant cooling in the US and Europe. The same tendency may occur in developing regions as their prosperity growth becomes more reliant on energy inputs and other water-intensive commodities in economic activities and final demand. Growth in population and urbanisation rates in these countries would also add an additional pressure on freshwater resources through higher municipal water demand by households. Global non-agricultural water uses are thus projected to grow fourfold for manufacturing and to more than double for thermal cooling and municipal uses (Marchal et al. 2011 p.216), with a higher expansion to occur notably in emerging economies.

With significant differences in the distribution of water endowments across world regions, the likely expansion in water demand in water-poor areas will lead to generalised and more frequent imbalances between demand and supply. The water deficits could be persistent, and they already are in the many rivers basins that are currently being over-exploited, and could also be exacerbated by climate variability and extreme weather events. The implications of disruptions to economic activities may be large-scale (WEF 2015) and could affect all sectors and households either directly through a reduction in water availability due to increased competition among users or indirectly through a reduction in supply of water-intensive commodities. As markets become increasingly integrated internationally, the impacts could also be felt outside these regions.

There are now many studies projecting the size of future demand in the face of socioeconomic development (Shiklomanov & Balonishnikova 2003; Vorosmarty et al. 2000; Shen et al. 2008; Shen et al. 2014; Wada et al. 2016; Wada & Bierkens 2014; Hejazi et al. 2013). However, the measurement of the economy-wide impacts of water shortages stemming from the gap between a growing demand and a limited water supply is still at an incipient stage. Most economic modelling has been dedicated to the analysis of water scarcity in relation to crop production (Rosegrant et al. 2002; Lotze-Campen et al. 2008; Calzadilla et al. 2010; Liu et al. 2016; Ponce et al. 2016; Winchester et al. 2016). The underlying assumption in these studies is that non-crop users are not affected directly by water deficits. At the same time, economy-wide analyses of water scarcity (Darwin 2004; Berrittella et al. 2007a) were either comparative-static or with limited elements in considering the relationship between socioeconomic development and water demand. Only the recent attempt discussed in Roson (2017) and disseminated in World Bank (2016) has tackled the link between socioeconomic development and water deficit, and the importance of water allocation across water users in conditions of constrained water use.

This paper aims to integrate within one CGE modelling framework the economy-wide impacts of demand-driven water scarcity by considering a wide number of water users. The effects of population and economic growth on a baseline water demand are broken down by user type through distinct demand patterns. These water demand dynamics are partially explained internally (crops and livestock) and partially described outside the model by considering changes in structure, scale and efficiency in the use of water by economic activities (thermal power production, industrial and municipal water supply). The unconstrained demand calculations based on the "middle of the road" SSP2 scenario are used to calibrate the RESCU-Water model for water scarcity simulations in the 2004-2050 horizon. Regions with excess water demand relative to a sustainable water supply level need to reduce this and implicitly re-allocate water across users according to alternative allocation methods. Given that water as an endowment is represented distinctly in the model, total supply is distributed across users through scarcity price signals according to differences in water productivity by using four alternative allocation methods with different user prioritisations. Furthermore, water-abundant regions can also expand their water withdrawals to take advantage of their competitive advantage through international trade.

2. Economic modelling of demand-driven water scarcity

2.1. 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 1 (see Appendix for calculation procedure). Considering that the model already determines water withdrawals for irrigation and livestock endogenously (see Nechifor & Winning 2017), the calibration is required only for the other three sectors – thermal electricity *elt*, industrial water supply *iwt* and municipal water supply *mwt*.

The nesting of inputs in the production functions of these sectors is similar as the introduction of water endowment input is done at the top level through a Leontief assumption (Figure 2). Therefore, the calibration is conducted in the same way for both and is done by using equation (1). The equation adjusts the annual levels of the water productivity factor $\phi_{Water,sai,t}$ associated to the water factor inputs.

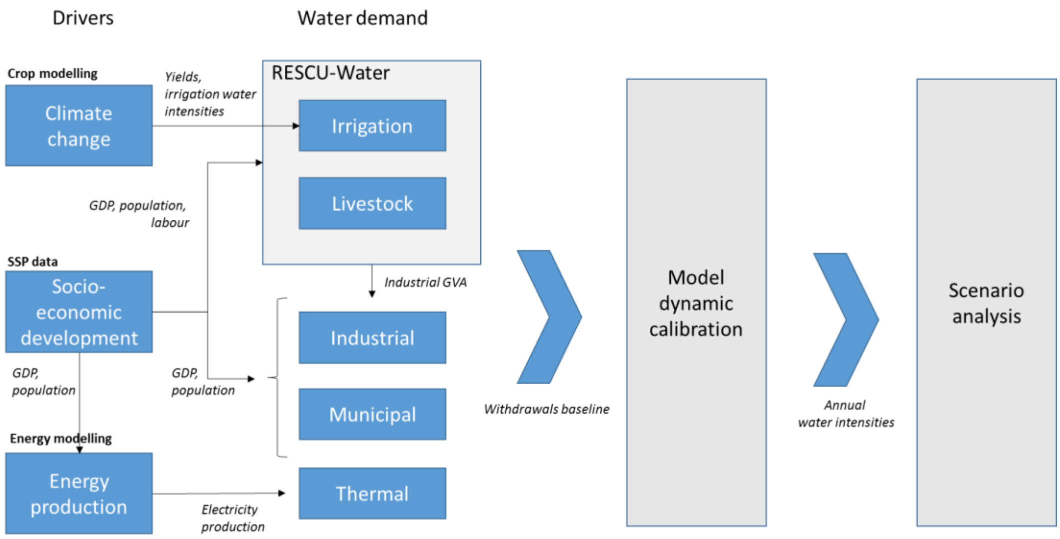


Figure 1 - Water withdrawals baseline model calibration

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

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

$XP_{sai,t}$ 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).

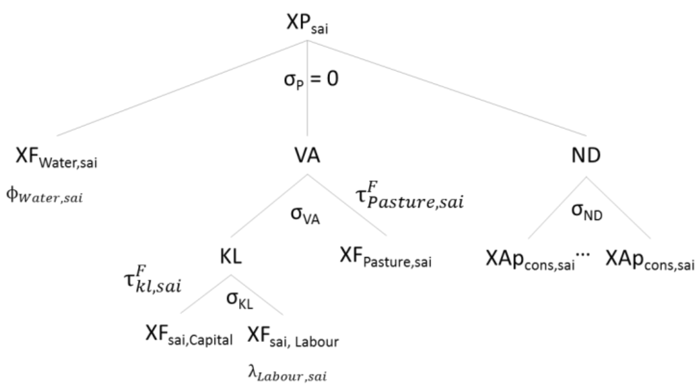


Figure 2 – Production technology of self-abstracting industries (sai)

2.2. Water scarcity analysis under different allocation regimes

The modelling of water scarcity implies a reduction in water availability for economic activities in regions which currently are 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. In these regions, water demand by self-abstracting sectors is endogenised through a specific model variable $XF_{Water,sai}$ (see Figure 2). For the "no water scarcity" model base case, total supply of water FS_{water}in each year t is specified to match the sum of all unconstrained demands $W_{sai,t}$. Therefore, with the calibrated $\phi_{Water,sai,t}$ values, the model generates sectoral demands $XF_{Water,sai}$ equal to $W_{sai,t}$ and sum up to the exogenously specified total supply FS_{water} at a water market price of zero i.e. no scarcity rents.

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.

By assuming a perfect mobility of water, the water allocation is done such that the marginal productivity across sectors is equal and that the shadow value of water is equal to the observable scarcity rents. Nevertheless, it is acknowledged that perfect mobility is difficult to obtain as this would imply the existence of economy-wide water markets, and that of intra- and inter-basin routing infrastructure. Therefore, the model allows alternative assumptions for water mobility through the introduction of different allocation methods:

1. Full allocation (FA) – the existence of one single water market within a region in which all water resources are tradeable between any given self-abstracting sectors
2. Limited mobility (LM) - only a fraction of 5% can be re-allocated across users based on scarcity price information
3. Fragmented markets (FM) – water use for crops and non-crop sectors is completely separated, and the reduction in water availability for each is proportional to the overall reduction in unconstrained withdrawals

4. Agriculture-last (AL) – only the use of irrigation water is constrained whilst non-crop users are free-riders

The first method (FA) implies that one single water market price applies to all users. Although examples of economy-wide trading of water rights do not currently exist, this method serves as a benchmark for water allocative efficiency. The second method (LM) assumes a reduced degree of mobility of water resources across the wider economic sectors. The assumption behind this market arrangement is that some trade-offs can occur between large water users enabling high-value activities to compensate for low-value activities for freeing up water resources. For instance, municipal water supply could expand water withdrawals by paying larger irrigation schemes for curtailing their unconstrained demand. The third method implies an allocation by separating water allocative efficiency across crop types from that across non-crop sectors. This method is also used in Berrittella et al. (2007b). The fourth method is that found in most water scarcity modelling and uses the assumption that agriculture is the user with the lowest priority. Water availability for irrigation is thus determined once all other unconstrained water uses have been deducted from the total sustainable supply. Water resources can still be mobile but only between different crop classes.

2.3. 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 (Wada et al. 2010; Rodell et al. 2009).

In light this regional heterogeneity, a few sustainability thresholds can be considered – TRWR, TRWR with environmental flows requirements deducted, and 40% of TRWR as a marker for severe water stress following the thresholds in Alcamo et al. (2003). 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 the environmental flow requirements (EFR) which in Figure 3 are considered to be 20% of TRWR as the lower bound for the estimations in Smakhtin et al. (2004). 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.

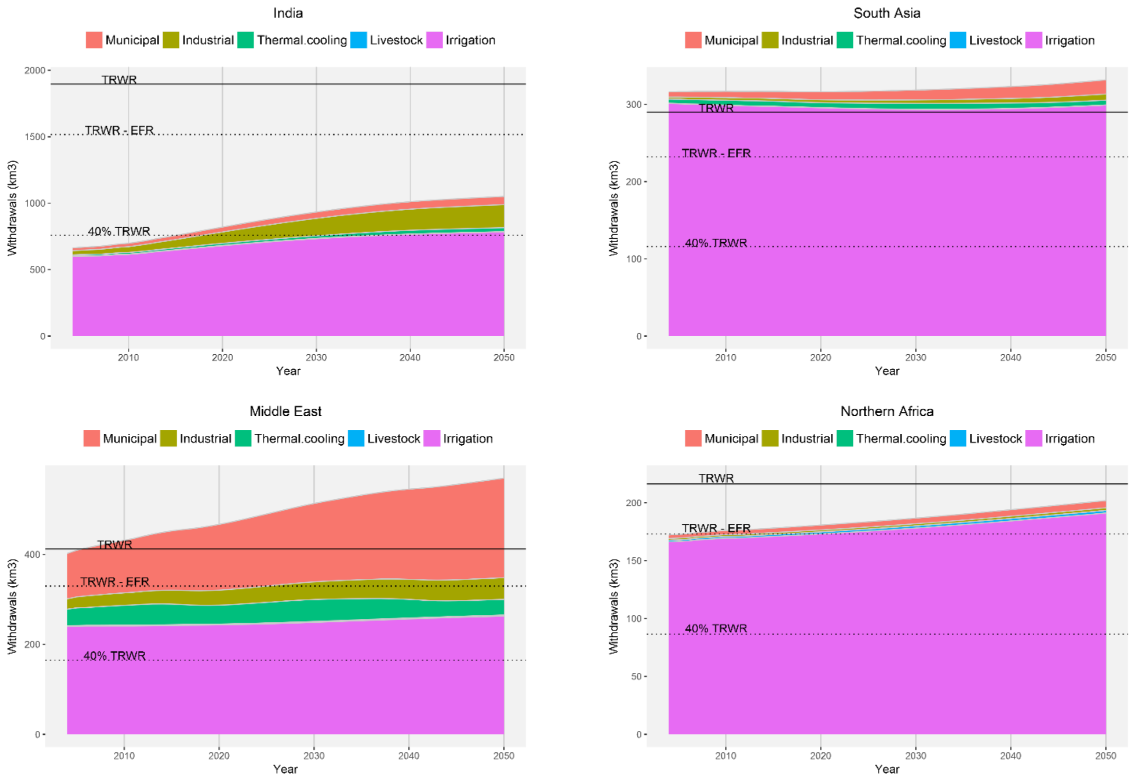


Figure 3 - Baseline withdrawals in regions with water deficits – SSP2

For each region a different sustainability level is set – India 40% of TRWR to prevent a significant further amplification of groundwater depletion[2], 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 80% threshold in the agriculture-last (AL) allocation method – the implied reduction in water availability for irrigated crops (234km^3) in 2050 almost matches the overall baseline demand for irrigation (263km^3). For the SSP2 "middle-of-the-road" baseline, Withdrawals in India are capped starting from 2015. South Asia is above the 80% standard already in the base year. Therefore withdrawals are gradually decreased down to meet this level by 2050. Withdrawals in Northern Africa are capped starting with 2005. The Middle East gradually decreases to 100% by 2050. At the end of the simulation period, the absolute reduction from unconstrained levels is 247km^3 for India, 108 km^3 for the South Asia, 151 km^3 for the Middle East and 16 km^3 for Northern Africa.

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

3. Results

3.1. Economic output impacts

The economic impacts of water scarcity are felt at an aggregate level mostly in water-scarce regions (Table 1), with only minor influences for the other regions. Nevertheless, by 2050, the negative impacts over world GDP measured in real terms could be in the order of 0.15%, or over $130bn GDP losses under the more inflexible water allocation regimes (limited mobility *LM* and market fragmentation *MF*). The impacts are reduced by two-thirds under the assumption of economy-wide water trading – the *FA* water market configuration, and are further reduced to negligible levels under the agriculture last *AL* regime. This finding is an indication that greater GDP impacts are obtained with increased constraints on the water availability to non-agricultural sectors.

Table 1 - Real GDP and Equivalent Variation impacts by RESCU-Water region in 2050

RESCU-Water region	LM			AL			FA			MF		
	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV
Middle East	*(1.797)*	(89.04)	(10.76)	*(0.020)*	(0.97)	(3.07)	*(0.761)*	(37.71)	(9.71)	*(1.841)*	(91.22)	(15.69)
South Asia	*(1.606)*	(7.07)	(1.51)	*(0.562)*	(2.47)	0.13	*(0.530)*	(2.33)	(0.10)	*(0.554)*	(2.44)	(0.63)
India	*(0.435)*	(33.19)	(7.80)	*(0.029)*	(2.24)	(3.53)	*(0.148)*	(11.26)	(0.96)	*(0.465)*	(35.43)	5.11
Northern Africa	*(0.022)*	(0.29)	(0.63)	*(0.003)*	(0.04)	(0.05)	*(0.012)*	(0.16)	(0.01)	*(0.010)*	(0.14)	(0.44)
Central Asia	*(0.016)*	(0.04)	0.00	*(0.001)*	(0.00)	(0.03)	*(0.003)*	(0.01)	(0.02)	*(0.006)*	(0.01)	(0.05)
Eurasia	*(0.009)*	(0.12)	0.05	*(0.000)*	(0.00)	(0.02)	*(0.002)*	(0.03)	(0.02)	*(0.006)*	(0.07)	(0.10)
China	*(0.002)*	(0.30)	(0.51)	*0.000*	0.05	(0.16)	*(0.001)*	(0.11)	(0.28)	*(0.004)*	(0.50)	(0.62)
Southeast Asia	*(0.002)*	(0.06)	(0.58)	*0.003*	0.10	(0.28)	*0.000*	0.00	(0.36)	*(0.005)*	(0.16)	(0.61)
Northern Europe	*(0.002)*	(0.19)	0.33	*0.000*	0.05	(0.05)	*(0.000)*	(0.03)	(0.09)	*(0.002)*	(0.23)	0.06
Southern Europe	*(0.001)*	(0.05)	(0.12)	*0.001*	0.08	(0.29)	*(0.000)*	(0.01)	(0.15)	*(0.002)*	(0.18)	(0.12)
Northeast Asia	*(0.000)*	(0.00)	0.07	*0.002*	0.09	0.05	*0.000*	0.02	(0.02)	*(0.002)*	(0.09)	(0.11)
USA	*0.000*	0.04	(1.19)	*0.001*	0.25	(2.69)	*0.001*	0.11	(1.69)	*(0.000)*	(0.03)	(1.74)
Sahel	*0.001*	0.00	(0.04)	*0.000*	0.00	(0.02)	*(0.001)*	(0.00)	(0.03)	*0.002*	0.00	(0.06)
Canada	*0.000*	0.01	(0.08)	*0.001*	0.02	(0.08)	*0.001*	0.01	(0.10)	*0.001*	0.02	(0.19)
North Latin Am	*(0.001)*	(0.04)	(0.21)	*0.001*	0.03	(0.11)	*0.001*	0.04	(0.23)	*0.002*	0.10	(0.55)
Australia&NZ	*0.001*	0.01	(0.01)	*0.003*	0.06	(0.12)	*0.002*	0.03	(0.10)	*(0.000)*	(0.01)	(0.07)
Southern Africa	*0.001*	0.01	(0.09)	*0.008*	0.07	(0.05)	*0.003*	0.03	(0.05)	*(0.003)*	(0.02)	(0.07)
Brazil	*0.002*	0.02	(0.28)	*0.005*	0.05	(0.47)	*0.003*	0.03	(0.32)	*0.001*	0.01	(0.30)
South Latin Am	*0.005*	0.03	(0.13)	*0.008*	0.04	(0.23)	*0.004*	0.02	(0.14)	*0.002*	0.01	(0.10)
Central Africa	*(0.006)*	(0.09)	(0.34)	*0.016*	0.25	(0.48)	*0.012*	0.18	(0.54)	*0.009*	0.14	(0.79)
World	***(0.146)***	(130.36)	(23.84)	***(0.005)***	(4.60)	(11.57)	***(0.057)***	(51.18)	(14.92)	***(0.146)***	(130.26)	(17.07)

Compared to the GDP reductions, the welfare impacts of water deficits are considerably lower in water-scarce regions in the LM, FA and MF cases. Depending on the incidence of scarcity over the different economic sectors, consumer prices can decrease leading even to positive EV outcomes

(India – MF, South Asia – AL). In the other regions, the impacts turn from positive GDP to negative EV as domestic prices of demand commodities increase due to the expansion of foreign demand.

In water-scarce regions, the incidence of the allocation regimes is dependent on the regional unconstrained water demand patterns in the baseline. The highest impacts in all four regions are obtained in the LM variant (Figure 4), with the highest impacts in the Middle East and South Asia. The MF produces similar results to LM in India and the Middle East; as opposed to the other two regions, non-irrigation water demand consistently increases its weight in overall withdrawals by 2050, and therefore the requirement for more flexibility in water re-allocation away from irrigation becomes more stringent. The AL method, affecting mostly crop production, leads to low GDP impacts except for South Asia where food sectors continue to have an important weight in the economy. Northern Africa is generally unaffected by water scarcity given the dominant role of irrigation in overall withdrawals persisting in 2050 - small volumes of water reallocation even within the mobiliy limits of the LM case (5% of total supply) are sufficient to ensure the resilience to water shortages of the economy as a whole. Therefore, there are important differences in the incidence of water scarcity between the first three (India, South Asia and Middle East) and this region.

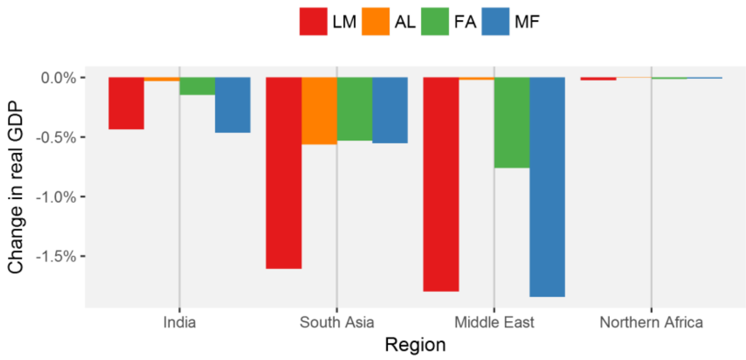


Figure 4 - Real GDP impacts by region and by allocation method

At a sectoral level, water scarcity impacts the activities with the highest dependency on water inputs given their substitution possibilities away from water use (Figure 5). Thus, crop production sees a drop of 5% or more in output in India, South Asia and the Middle East with cascading effects over the processed food sector. As explored below, irrigated crop production drops by even higher rates with rainfed production only partially offsetting this effect. The same applies to the power generation sector – thermal electricity has the highest reduction in output of all activities, with the production mix switching towards non-thermal power.

Industrial sectors with inflexible production functions with regard to industrial water use (chemicals, primary energy, mining, manufacturing, paper and construction) are also affected but to a lower degree. The typical drop in output for these sectors for the LM method is 2% in the Middle East, 1% in India and 3.5% in South Asia. In the other water allocation methods, the output reduction is lower although still significant for the MF method, negligible for FA and even positive in some cases for AL. In Northern Africa, although the impacts of the different allocation regimes are generally negligible, industrial output increases in the LM case with more mixed outcomes for the other methods. In the LM regime, the limited flexibility to optimise water allocation within crop production across the different crop types determines an overall crop output reduction with a re-allocation of water resources to the non-crop sectors.

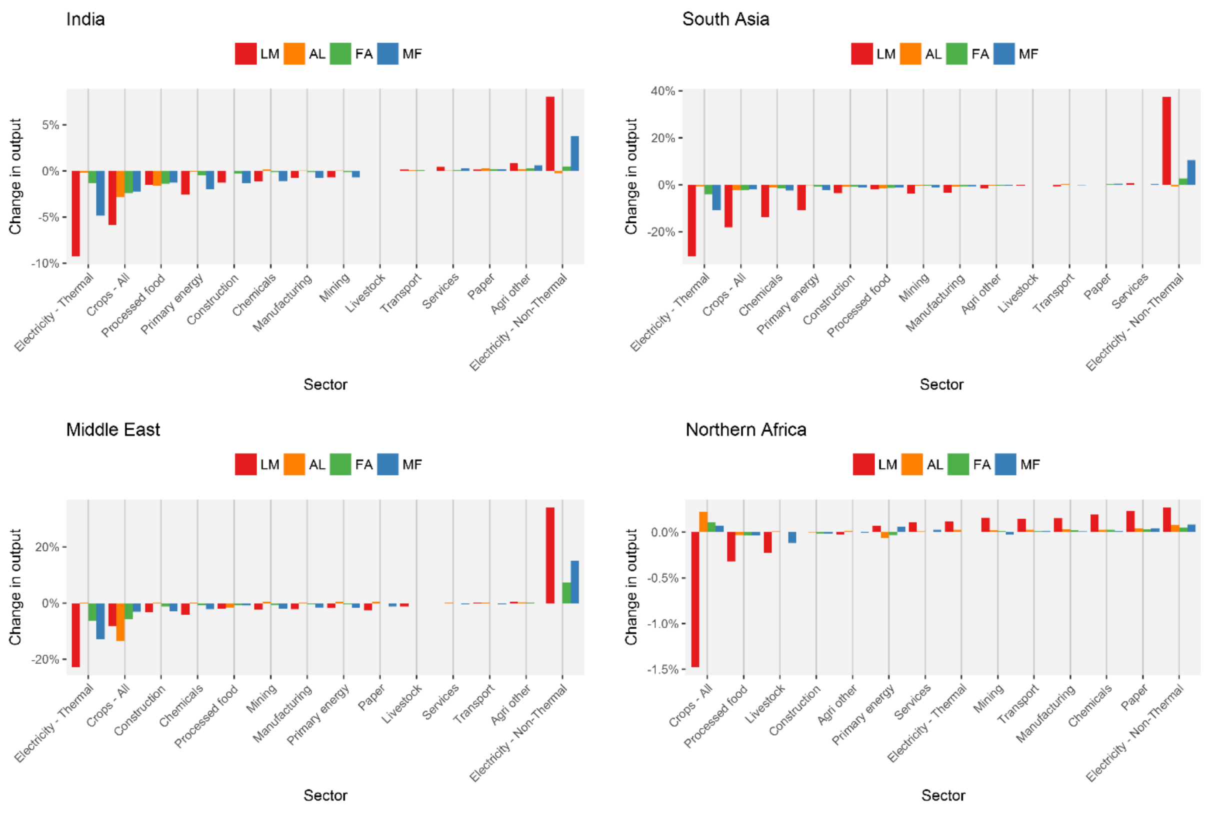


Figure 5 - Sectoral output impacts in water scarce regions

3.2. Water scarcity rents

Water scarcity rents revealed by the market price of allocable water resources differ across methods (Table 2). The values obtained in the LM case are the highest as the competition between users is limited by the low mobility of water endowments. In the other cases, water scarcity prices are much lower with the smallest values obtained in the FA case. These values also represent the rents for the highest water allocative efficiency. For MF, as irrigation and non-irrigation water uses are completely separated into two water markets, the price for irrigation uses are lower than those for non-irrigation. These differences mark the variation in marginal productivities between the two user types with possibilities of water re-allocation from crops to other non-agricultural sectors for further improvements in water allocative efficiency.

The AL case generates slightly higher rents than FA, although the GDP impacts are lower. Despite the potential efficiency gains in re-allocating some water volumes from non-crop sectors, the decline in crop output due to water scarcity determines a shift of other means of production (capital and labour) to other sectors improving the economic outcomes of the overall factor allocation. Furthermore, as water scarcity rents are not reflected in the cost structure of non-crop sectors, these will have a further competitive advantage as free-riders by expanding their water uses beyond the levels from the FA case.

Table 2 - Water scarcity rents in 2050 by region and by allocation method ($/m^3)

Region	LM	AL	FA	MF	
				Irrigation	Non-irrigation
India	4.568	0.067	0.055	0.049	0.258
South Asia	4.460	0.042	0.040	0.037	0.129
Middle East	5.542	0.431	0.119	0.053	0.246
Northern Africa	0.962	0.003	0.003	0.003	0.064

3.3. Water withdrawal changes

The changes in withdrawals by self-abstracting sectors (and the changes in supplied water use by the underlying municipal and industrial water users) are determined by the trade-offs between these economic activities leading to different outcomes across the four allocation methods. Given the high water intensity of irrigated crops, the bulk of withdrawals reduction to reach the regional sustainability thresholds is ensured through a significant decrease in irrigation withdrawals (Figure 6). Nonetheless, for India and the Middle East, a noticeable demand cutback in volumetric terms also occurs in the second most important self-supplied sector - industrial water supply in India and municipal water supply in the Middle East.

In relative terms (change rate from baseline), in the LM method, municipal water withdrawals (despite a high water productivity) decrease at comparable rates with irrigation most revealing thus the larger scope to reduce water demand of the underlying supplied users (services and households). In the MF case, the higher flexibility in water allocation between non-crops users triggers a larger decrease in municipal water use to the benefit of the other sectors (thermal electricity, industrial water and livestock). Further on, the single water market configuration (FA case), determines a sharp reduction in water uses by irrigation and an increase in water availability for all other sectors (Middle East and South Asia) or notably for thermal electricity and municipal water (India). As baseline withdrawals for thermal electricity in Northern Africa are very low compared to other uses, water from irrigation is mainly redirected to industrial and municipal uses.

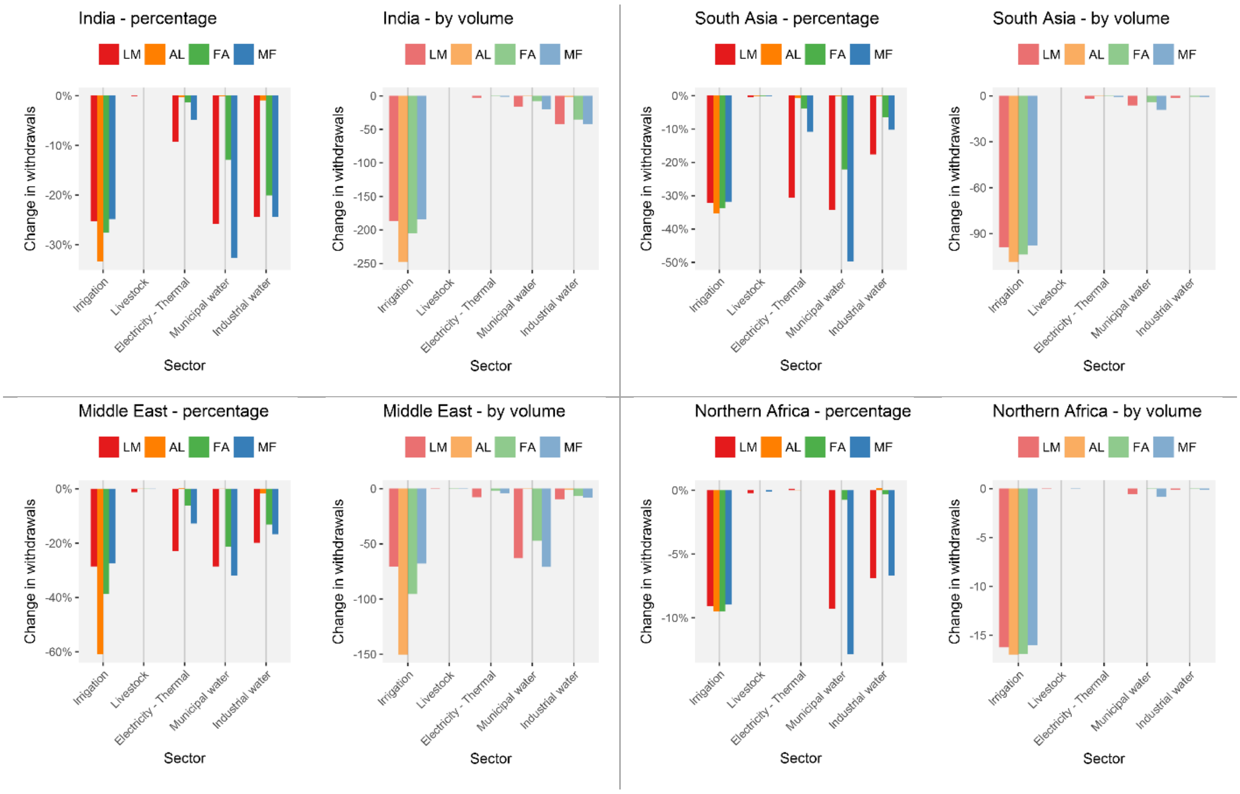


Figure 6 - Withdrawal changes by region and by self-abstracting sector in relative and absolute terms

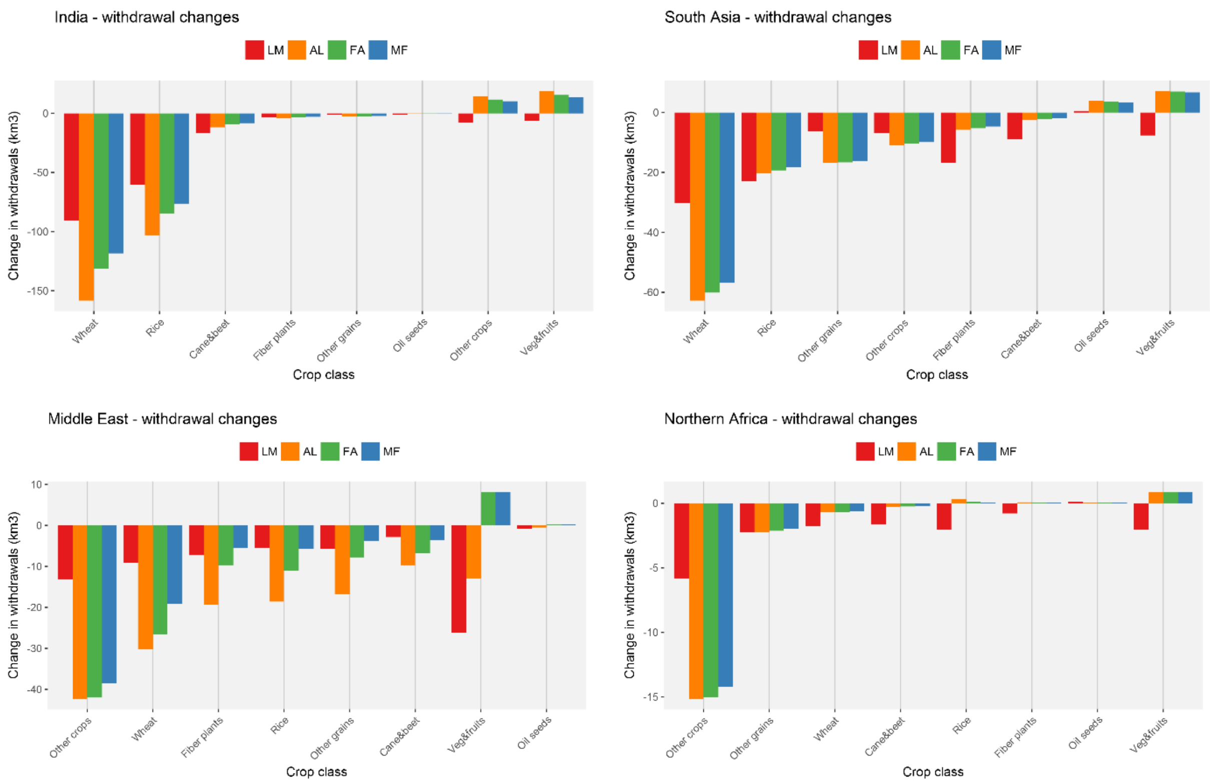


Figure 7 - Withdrawal changes by irrigated crop type in 2050

Changes in the water use patterns across the different crop types reflect the differences in crop water productivities. Thus, water demand is considerably reduced in water-intensive crops (Figure 7). Withdrawals for *rice* and *wheat* in India decrease by more than 250km^3 (the equivalent of total required reductions) for *wheat* in South Asia by 60km^3 (half the total required reductions) , for *other crops* in the Middle East by 40km^3 (a quarter of total required reductions) and for *other crops* in Nothern Africa by 15km^3 (as much as total required reductions).

3.4. Food security

Water scarcity highly impacts crop production with some differences across crop types (Figure 8). In India, *rice* and *wheat* are touched the most with decreases in output of over 15%; in South Asia, the same crops drop by more than 20%, whereas, in the Middle East, *other crops*, *fiber plants* and *wheat* can have a decrease of more than 30%. Northern Africa is less affected with only *other crops* having a marked decrease next to 10%.

The incidence of water deficits is dependent on the water allocation method with a clear contrast between LM and the other three variants. In this regime, crop production generally decreases across all crop types and regions, leading to an overall increase in crop market prices[3]. Irrigated production is constrained by water deficits, similarly to all non-agricultural water users, and by the lack of flexibility to re-distribute water across crop types. Although the fall-back from irrigated to rainfed production is possible, the substitution between the two growing methods is not sufficient to fully counteract the drop in output of irrigated crops.

The other three allocation methods lead to a more noticeable re-allocation of water resources across crop classes marking the opportunity to improve the baseline water productivity across irrigated crops. The scarcity impacts over the output of some crops are thus alleviated in the detriment of others. In India, *rice* and *wheat* production further decline in favour of additional water use and implicitly an output increase in all other crop types. In South Asia, the highest output decline occurs for *other crops*, *wheat* and *rice*. In Northern Africa, a significant decrease in production is obtained for *other crops* with limited negative impacts for *cane&beet* and *other grains*. In the Middle East water is re-allocated from most crops to sustain the irrigated production of oil seeds and *veg&fruits*.

The largest contrast is obtained in the AL case where competition over water use between crop classes is exacerbated through the unrestricted withdrawals outside irrigation. As the water volumes available for crop production are the lowest among all four allocation methods, the differences in

[3] Crop market prices correspond to the Armington good prices of each crop class and thus combine both domestic and imported varieties

terms of water productivity between crop classes become more evident. The Middle East is the exception where trade-offs are limited due to a lower variation in the baseline water productivity levels across crop classes but also to international trade (see virtual water trade section below).

The water market fragmentation MF offers some protection to crop production decline by limiting the volumes of water to be re-allocated to non-crop users. Hence the output and price outcomes are improved in MF compared to the single market FA case. The differences between the incidences of water scarcity across crop classes are also reduced. In this regard, AL and MF could be considered two opposing allocation methods - the first overlooks the importance of crops and food security, whilst the latter imposes a volume available for irrigation in spite of differences between water productivities of specific crop classes and other water users.

In India, the effect of the decrease in domestic production over crop market prices is the most pronounced. This price response obtained across the four allocation methods is an indication that international trade does not have a significant role in reducing the food security impacts especially for the main crops of *rice* and *wheat*. As the imports dependency ratio in the baseline is low (Figure 9), the Armington assumption of international trade prevents a significant expansion of imports despite the increase in market prices.

In contrast, imports in the Middle East and South Asia have an offsetting effect on prices. The import dependency of *wheat* in the Middle East grows from 24% in the baseline to 36% for AL, and from 9% to 43% for *rice*. Similarly, in South Asia, the dependency grows from 18% to 33% for *rice*. Imports of other crop classes also increase in importance – *other crops* in South Asia; oil seeds, *fiber plants*, *other crops* in the Middle East and *other crops* in Northern Africa. These are all cases for which the baseline dependency ratio is non-negligible and for which output is negatively affected by regional water deficits.

Figure 8 – Water scarcity impacts on crop production and prices

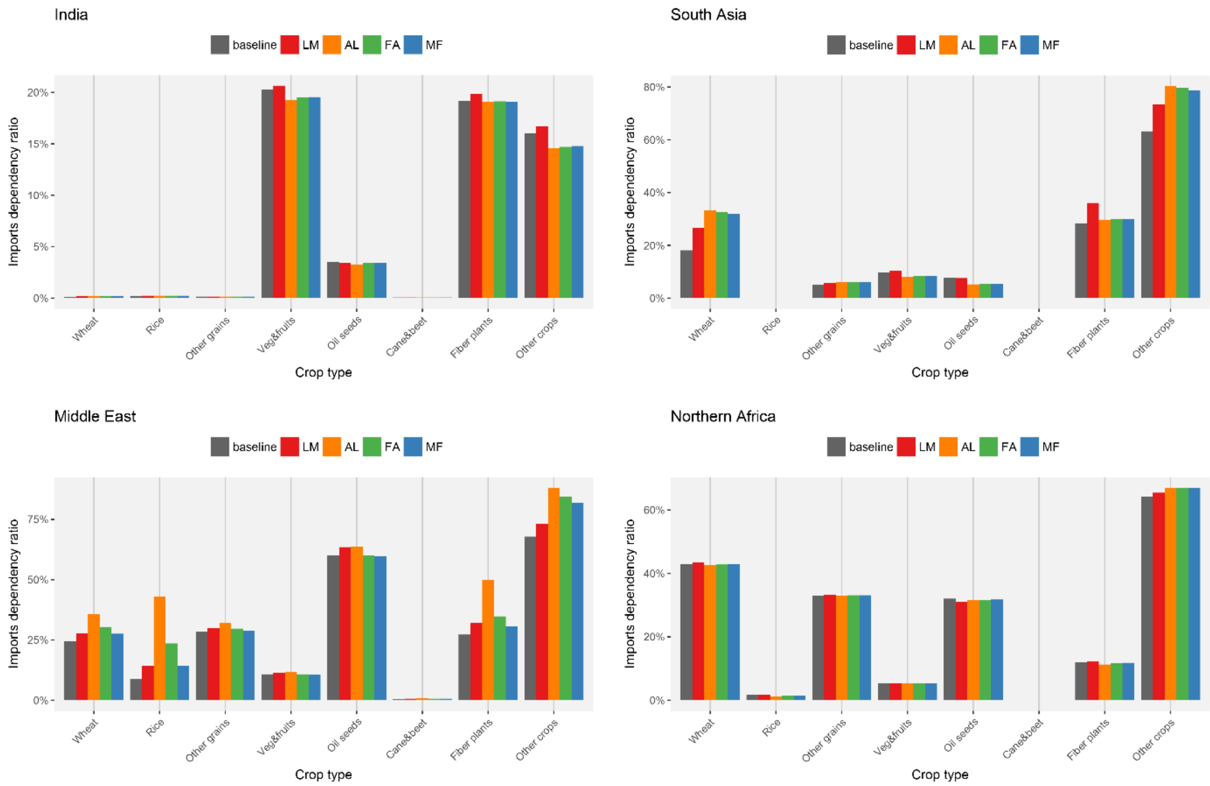


Figure 9 - Crop imports dependency ratio by region

3.5. Virtual water trade

The impacts of water scarcity over global virtual water trade are limited to the flows of the four regions and are mostly driven by crop trade (Figure 10). The largest changes occur in the Middle East, where the net imports grow by 26km^3 in the AL case (Figure 11), or 7% of global virtual water trade in the baseline[4], indicating the importance of international trade in addressing the drop in domestic crop production. This increase in imports converts the region from being a net exporter of water (19km^3 of net exports in the baseline) to a net importer (8km^3 of net imports in AL). In Northern Africa, although the changes are small in absolute terms (1.5km^3), these account for 10% total required reductions in withdrawals in the region. South Asia has a noticeable increase in net imports only in the LM case determined by increased imports of *veg&fruits* and *fiber plants*. At the same time, some increases in net exports are obtained in India in the AL and FA case, as a marker that international trade can further increase the impacts of water scarcity, notably over food security, through exports of water-intensive commodities stimulated by increases in foreign demand.

[4] Global virtual water trade in 2050 for SSP2 is 372km^3 and includes the embedded water in both crop and non-crop traded commodities

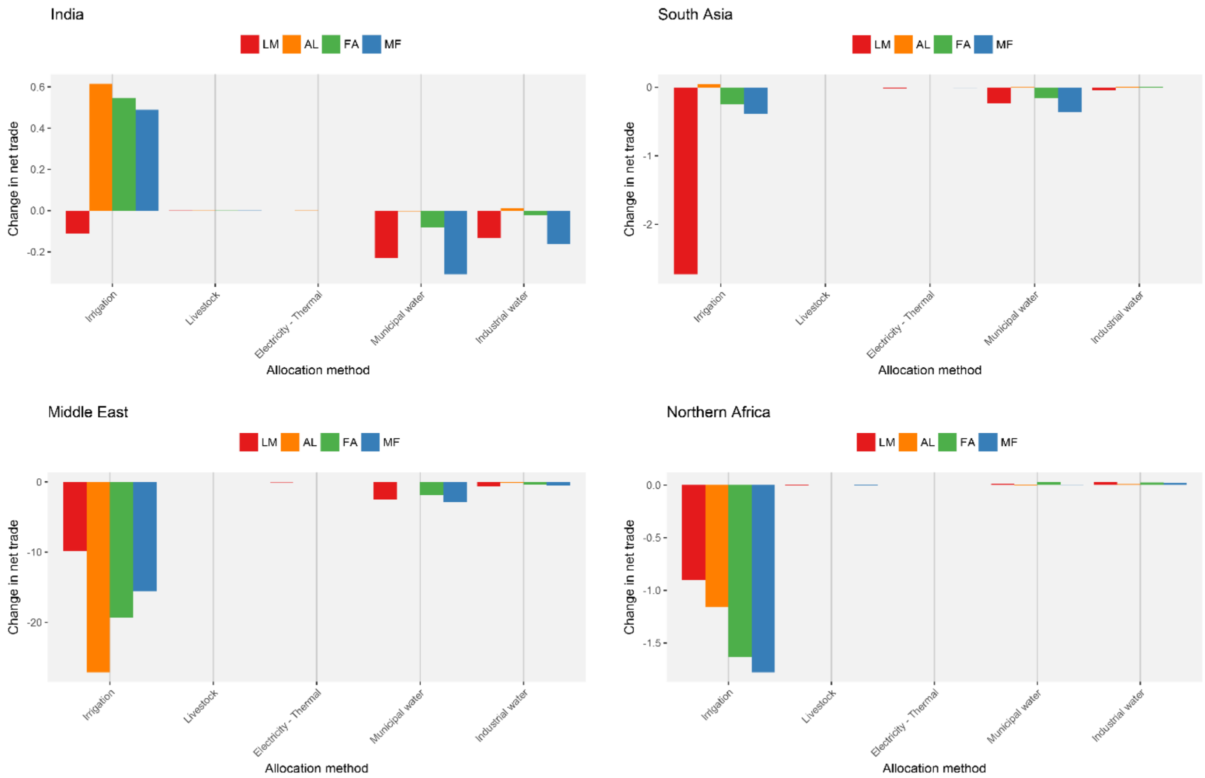


Figure 10 - Changes in net trade of virtual water by water category

Other visible changes in the net trade of virtual water outside crops are mainly linked to commodities from activities using industrial and municipal water. As expected, AL does not have any trade impacts given that water deficits do not constrain non-crop sectors. In the other allocation methods, virtual water trade associated to services (municipal water users) increases in all regions, except for Northern Africa, indicating international trade as a further adaptation mechanism to water scarcity. The same applies to the trade in commodities from industrial activities. However, the overall change in virtual water imports attached to industrial commodities is lower than that for services. Changes in the flows related to thermal electricity are limited by the low levels of electricity trade between regions in the baseline.

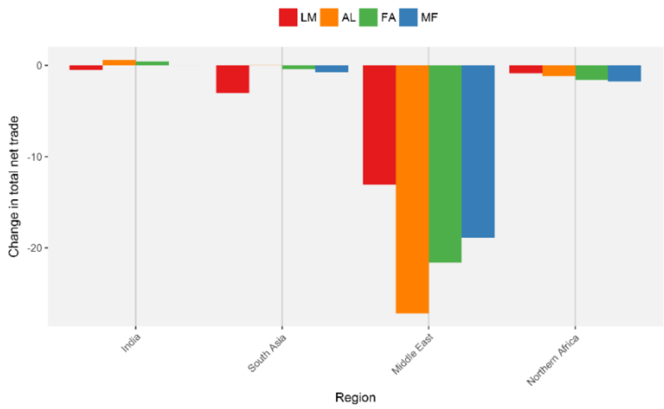


Figure 11 - Changes in regional net trade of virtual water by allocation method (in km^3)

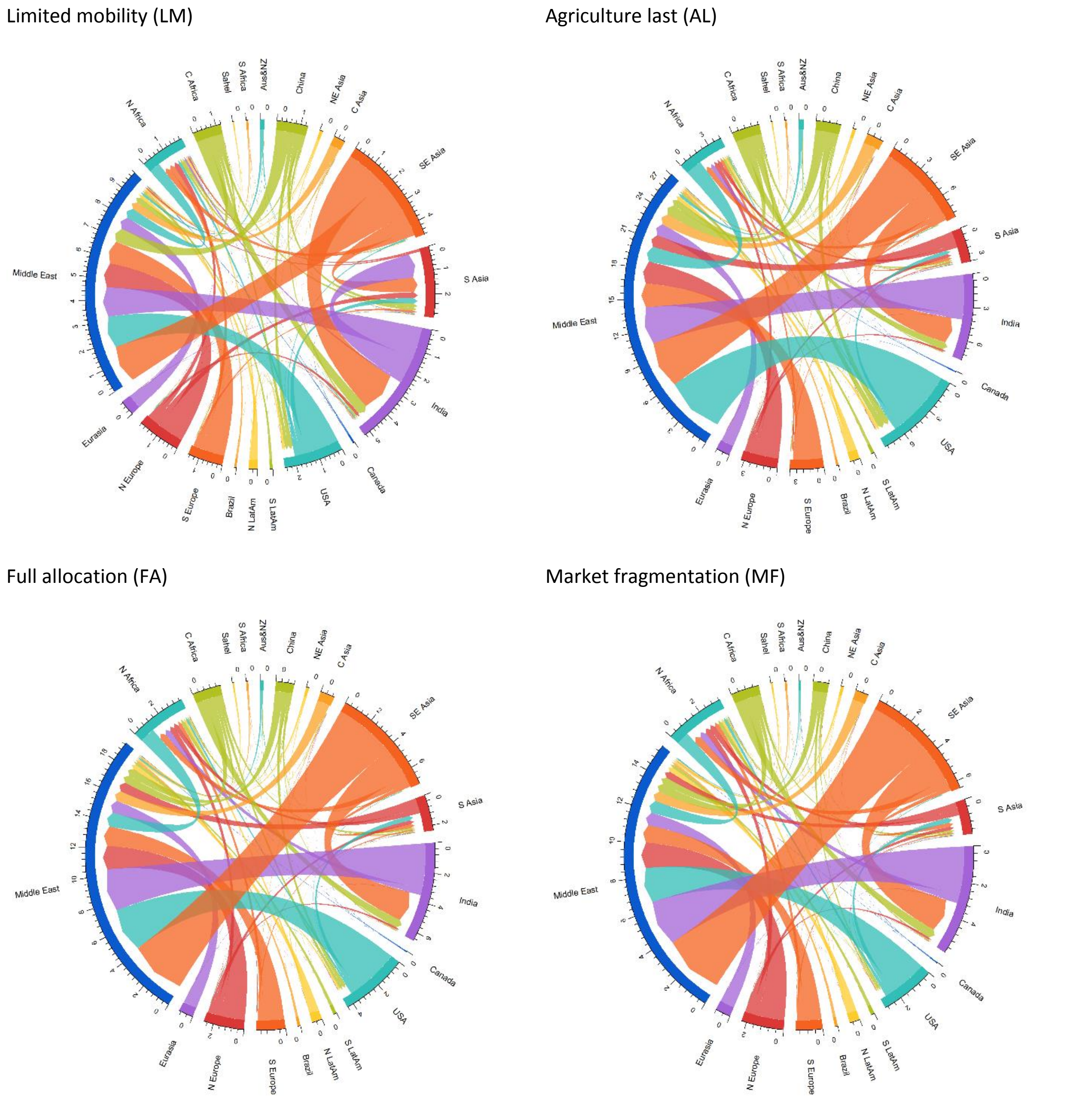


Figure 12 - Changes in virtual water trade flows of crops – net values by trading pair (in km3)

The Middle East has a dominant role in the virtual water trade changes with its net imports increasing across all its trading partners in all four allocation methods (Figure 12Figure 11). The analysis of trade flows by pair also shows the importance of this region in the net trade of the other three water-scarce regions - most increases in virtual water exports of India, South Asia and Northern Africa are absorbed by the Middle East.

Other important sources of virtual water include the USA, Southeast Asia, Central Africa and Northern & Southern Europe. Nevertheless, this growth in net exports of regions without water use constraints does not lead to a significant growth in water withdrawals in these regions – the total increase in 2050 in outside water-scarce regions is 2.8 km^3 for LM, 4.5 km^3 for AL, 2.3 km^3 for FA and

2 km^3 for FM. This low expansion is an indication that instead of extending crop production, these regions redirect more domestic production towards exports.

4. Discussion

The obtained results indicate different outcomes for economic activity, welfare and food security across the four allocation methods considered. In essence, the LM method leads to a general decrease in economic activity with limited re-adjustments of production as a consequence of water availability constraints acting on water-intensive sectors. The AL allocation determines a neutral impact over non-food sectors and, depending on the exposure of the economies in water-scarce regions to food sectors (crops and food processing), determines a low impact on GDP, as non-crop water users act as free-riders. However, in the AL case, production of staple crops (*rice*, *wheat* and other grains) is the most significantly impacted with important implications for food security. In the MF variant, the separation of water uses by crop and non-crop users enables the availability of a guaranteed water volume for crops and therefore ensures some protection for food security – in this case, alterations to the crop production mix and changes in crop prices are the lowest. Nevertheless, MF leads to higher GDP impacts as the divergence in marginal water productivity between crops and other sectors remains significant, as revealed by the fourfold difference between the water scarcity rents of the two user types. In the FA case allowing full mobility of water resources across economic, the GDP and food security impacts are moderate relative to the other allocation methods.

4.1. GDP versus food security

Table 3 summarises these findings and reveals two important contrasts in the incidence of water scarcity across the two dimensions of GDP and food security. The first contrast is between diversified economies (India and the Middle East) and those with a significant food sector in the regional GDP (South Asia). Economies with a sizeable agricultural and food processing sector do not show an important variation in GDP impacts across the three allocation methods based on water productivity differences (AL, FA, MF) – the drop in crop production has a significant negative knock-on effects over the other sectors. The second contrast applies to diversified economies and refers to the difference between these allocation methods and that of a more prescriptive allocation (LM) where most water uses are pre-determined. For the former group of methods, the GDP - food security impacts are antisymmetric, producing either "high-low", "moderate-moderate" or "low-high" outcomes. For the latter method (LM), the impacts are high across both dimensions. These observed trade-offs between GDP and food security make a case for a general equilibrium approach rather than a partial- crop-focused analysis. Water scarcity and the region-specific sectoral interlinkages lead to different outcomes depending on the allocation method used.

These trade-offs are essential in the discussion related to the impacts of water scarcity over prosperity. By only taking into account GDP deviations from the baseline, it could be inferred that water deficits effects are not so much a matter of availability but one of how water resources are managed considering the relative water productivities of users. This conclusion is also coming out of the economic modelling results in World Bank (2016) and is also captured here through the differences between LM and the other three productivity-based methods. However, the results also reveal that the food security impacts are large and could be felt much more by the low-income household and by the rural population on whose livelihoods depend on crop production.

Table 3 - GDP and food security impacts comparison across economy types by water allocation method

Economy type	GDP impacts			Food security impacts		
	High	Moderate	Low	High	Moderate	Low
Diversified economy	LM, MF	FA	AL	LM, AL	FA	MF
Significant food production sectors	LM	AL, FA, MF	n/a	LM, AL	FA	MF

4.2. Drivers of GDP impacts

The economy-wide impacts of water scarcity are strongest in conditions of limited possibilities of water re-allocation across economic activities (LM case) with values close to 2% of GDP for the Middle East and South Asia. The most affected areas are the self-abstracting sectors (crops, water distribution sectors and thermal power), with cascading effects on the water-intensive industries supplied with industrial water (primary energy, chemicals, manufacturing, mining and paper). However, livestock production is much less affected due to the sector's high water productivity compared to all other water users. The re-allocation of non-water factors of production (labour and capital) in sectors with low or no water inputs is limited with only singular cases of visible increases in output (generally non-thermal power).

Nevertheless, these negative effects are alleviated by the substitution effects which can occur between similar activities (irrigated and rainfed crop production, thermal and non-thermal power generation). Therefore, whilst the substitutability between varieties of market commodities remains valid[5], the capacity of production to adjust over time especially in the power generation systems is important. The model assumes a perfect mobility of capital and labour. Hence, the switch in production from one type to another is frictionless. However, considering the long lifetime of power generation assets, the perfect mobility of capital could be challenged through a CET capital mobility

[5] Irrigated and rainfed crops could be considered homogenous and therefore close to perfect substitutes; thermal and non-thermal power can be imperfect substitutes as, for instance, thermal power technologies could be a more reliable solution for baseload power production whereas non-thermal (solar and wind) technologies produce electricity intermittently.

specification. This imperfect mobility assumption could thus further increase the economic impacts of water scarcity over the overall power generation with knock-on effects across the other economic sectors.

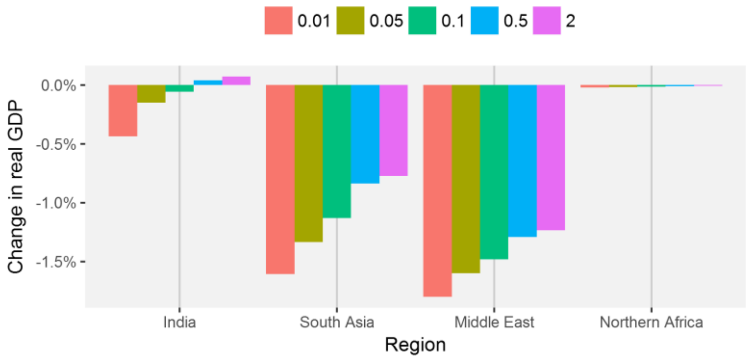
Another alleviating factor is the household recycling of revenue of water rents - the loss of income due to a water-constrained economic activity is partially counterbalanced by an increase in income from scarcity rents. This revenue recycling is a different specification than that in Roson (2017) where water scarcity translates into a loss in total factor productivity across sectors based on the initial relative water productivities, and thus household income is generally reduced.

Another important determinant in GDP that also impacts welfare and food security is the combination of the distribution of baseline sectoral water productivities and the size of water demand in low productivity sectors. Regions with low productivity sectors also accounting for the largest share of withdrawals (India with *rice* and *wheat*, Northern Africa with *other crops*) make most of their water demand reductions in these activities. Therefore, the economic impacts are concentrated within a small number of crop growing activities leaving the other parts of the economy less water constrained. Again, the negative impacts on irrigated production are partially offset through substitution with rainfed production, and therefore the localised effects on a few economic activities are further attenuated.

The obtained changes in withdrawals to meet the sustainability threshold reflect both differences in water productivity and the adaptability of specific sectors to water deficits. Among the self-abstracting sectors (which treat water as a perfect complement to other inputs), livestock and thermal power see the lowest reduction in withdrawals as an indication of their low water intensity. At the same time, in spite of a superior water productivity, municipal water is a more important source of demand reduction than industrial water, marking the larger flexibility of the underlying municipal water users to substitute water with other inputs.

Notably in diversified economies, the size of GDP impacts is determined by the sectoral impacts of water-intensive industrial users. In the model specification, these sectors have a low substitutability of water with other inputs and factors. With an increased adaptability which can come from the adoption of more water-efficient production processes, the impacts could be significantly reduced (Figure 13) as indicated by the results of a sensitivity analysis on the key elasticity of substitution σ_{ND2} between industrial water inputs and all other intermediate goods. Therefore, the magnitude of effects on economic activity in a scenario with a low flexibility in the technological choices warrants more research into the sector- and region-specific means of improving water productivity in industrial activities. An example of how the water savings potential varies between regions is given in McKinsey (2009 p.73).

Figure 13 - 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 Results section

4.3. Significance of international trade

The attenuating effect of international trade on food availability is also limited. This is conditioned by the flexibility in switching consumption from domestic to foreign varieties, given the Armington specification of trade. Regions which already have a high share in imports of water-intensive commodities (Middle East and Northern Africa) benefit more from virtual water inflows, whilst regions being self-sufficient from a crop production standpoint have a limited import expansion. The Armington elasticities[6] are thus a blocking factor to the expansion of imports of water-intensive commodities where the baseline regional imports are low. Furthermore, the simultaneous occurrence of water scarcity across regions leads even to an increase in pressure over low water-productive sectors in some regions in favour of other regions e.g. due to the size of initial trade links, India exports irrigated crops to the Middle East impacting, thus, its own food security.

4.4. Comparison to other studies

The GDP and EV impacts obtained in Roson (2017) are significantly higher than the results obtained in this study, with a GDP decline, for instance, at or well above 4% in the Middle East[7]. An explanation for these differences consists in the much larger water deficits considered and is justified by higher unconstrained withdrawals in water-scarce regions by 2050. These differecens are mainly coming from a considerable expansion in irrigation water demand as this is calculated on a "top-down" basis. Another explanation is that in Roson (2017) there are relatively low means of endogenous adaptation to water scarcity as output is constrained by pre-determined changes in

[6] Values derived from the GTAP database

[7] Depending on the water allocation scenario; this decline could be as much as 14% in the low mobility case

total factor productivities. In RESCU-Water, as discussed above, the advanced specification of water uses and the substitution possibilities between low and high water-efficient varieties of the same commodity allow for more resilience of the regional economies to water scarcity.

In the static-comparative simulations using GTAP-W1 (Berrittella et al. 2007b), regional water demand is reduced by only a small fraction, leading to much lower GDP and sectoral impacts. Only a few sectors across water-constrained regions exceed a negative impact of 1% (mainly crops). At the same time, similarly to RESCU-Water, the sectoral output results indicate a re-allocation of non-water resources across economic activities towards sectors with little or no supplied water inputs.

4.5. Limitations

Whilst the concomitant incidence of water deficits is determined for a number of regions, some other regions were not considered as water scarce due to their more localised water deficits (China, Southern Africa, USA, Australia). The coupling of RESCU-Water with other advanced hydrological models comprising spatially-detailed information on water-use constraints relative to the topology of users could enable the inclusion of other regions in the analysis. Furthermore, the water supply limits imposed are applied to a regional level and do not take into account basin-specific constraints even in the four regions considered. Hence, in this regard, a further qualification of sustainable withdrawal thresholds could also be done using spatial modelling.

The water deficit calculation is partially based on top-down demand projections (industry and municipal water use) which are not empirically validated but are derived by building on previous work. The comparison of results shows a good agreement for global withdrawals and developing regions. However, some differences occur regarding the industrial water uses in currently developed regions. As the simulations do not imply constraining any of the high-income regions, the CGE results are not influenced by a potential overestimation of water uses in industrialised regions. At the same time, there are significant differences even in between projections with empirical validation (see Wada et al. 2016) indicating that more work should be done in the direction of establishing water use baselines for economic modelling simulations.

The positive impacts of climate change over GDP under water scarcity in diversified economies show that the effect of non-water resource re-allocation is strong, and indicates that climate change is largely an issue for food security. Nevertheless, it should be acknowledged that other sectors could also be directly impacted by changes in environmental operating conditions. For instance, as outlined in Wada et al. (2016), the demand for water for thermal cooling could increase with ambient temperature. Furthermore, the impacts in this study exclude the implications of climate change over other the supply of other factors – the reduction in capital and land availability and that of labour productivity as in Parrado et al. (2017) or Bosello et al. (2007).

Regarding food security impacts, the conclusions are derived from model results on crop availability and prices. Details on the incidence of crop production mix over malnutrition are not available as these would require a further consideration of the relationship between the food value chain informing the final food demand composition and the calories intake by different population groups.

Regarding the coverage of allocation methods, the model mostly makes use of differences in water productivities in re-distributing available water resources to the different users. At the same time, the different principles used allow for a prioritisation of certain users in the detriment of others. A further analysis could be conducted in the direction of food security policy by considering among other things programmes for increased irrigation water efficiency or a larger availability of water for crop production (possible through the MF method by shifting the burden of reducing withdrawals to non-agricultural sectors). However, considering the global level of the analysis in this study, it would be difficult at this stage to introduce other relevant methods which do not embed water productivity information but are mostly prescriptive in nature.

5. Conclusions

This study used the future evolution of unconstrained water demand driven by socioeconomic development as a starting point to determine the impacts of water deficits over economic activity, welfare and food security. By comparing the unconstrained demands with regional thresholds for sustainable withdrawals, four regions emerged as water deficient due to their growth in water demand across five water use types (irrigation, livestock, thermal cooling, industrial water and municipal water) – India, South Asia, Middle East and Northern Africa. The reduction in water demand in these regions was enabled using four different water allocation methods.

In a world with perfect water mobility, an allocation based on differences in water productivity between sectors leads theoretically to water allocative efficiency (FA method). However, this does not guarantee the best aggregate economic outcome due to the interaction with other factors of production. Changes in sectoral output due to water scarcity also determine a re-allocation of non-water resources across the economy. With agriculture also having a low factor productivity of capital and labour, the water allocation methods determining the highest re-distribution of resources to the other sectors lead to the lowest GDP impacts. Therefore, the method treating crops as lowest water priority users (AL method) improves most the output prospects of non-food sectors in the detriment of crop production and food processing.

At the same time, the scale of economy-wide impacts are dependent on the size of sectors with low-water productivity (economic diversity), the size of water uses in these sectors and the flexibility of important water users to substitute from water inputs in conditions of water scarcity. Furthermore, given the Armington specification adopted in the RESCU-Water models specification, the use of international trade as means to alleviate the impacts of water deficits are conditional upon the baseline import dependency of water-intensive commodities– the lower the ratio, the lower the changes in net imports of virtual water trade under water scarcity.

The food security impacts are pronounced across all methods considered, with the lowest negative outcomes obtained through the isolation of water demand in irrigation from all other water uses (MF method). In the model simulations, this implied a uniform reduction in crop and non-crop water availability. More protection to the food value chain could be obtained by ensuring more water availability for crop production and less for other uses. However, this would implicitly lead to a higher negative GDP impact as a trade-off.

By using a comprehensive CGE framework focused on the economy-wide uses of freshwater, the results in this study offered an extended insight into the economic impacts of alternative water allocation regimes. The results presented here go beyond most of the previous work which focused on the relationship between water scarcity and agriculture and which only took one water management method into account (Calzadilla et al. 2013; Liu et al. 2016; Ponce et al. 2016). Furthermore, the analysis outputs are an important expansion into the topic of trade-offs between aggregate economy-wide impacts and food security, an area under-explored even in the most recent economy-wide CGE modelling work (Roson 2017).

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Annex - Establishing a global water demand baseline

Baseline calculation for 2004-2050

By using 2004 levels obtained through the water accounting data from EXIOBASE (Lutter et al. 2013), 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 socioeconomic development (Flörke et al. 2013; Hanasaki et al. 2013; Wada & Bierkens 2014; Roson & Damania 2016).

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 Nechifor & Winning (2017), socioeconomic 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 Nechifor & Winning (2017) 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.

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 assessment through biophysical modelling. 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 (Wada et al. 2014) as a product of the scale of economic activity, economic development (ED) and technological change (TC) (A1). 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* (A2). Last, the TC component reflects the tendency of technologies to become more water efficient over time. In line with the approach in Wada et al. (2016), 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 (Anandarajah et al. 2011) for SSP2 and are consistent with the power production projections used for the thermal cooling water calculations explained below.

$$IWD_t^r = IWD_{2004}^r * \frac{GVA_{r,t}^{ind}}{GVA_{r,2004}^{ind}}^{0.5} * ED_t^r * TC_t^r \quad (A1)$$

$$ED_t^r = AVERAGE\left(\frac{GDP_{r,t}^{pc}}{GDP_{r,2004}^{pc}}^{0.5}, \frac{EN_{r,t}^{pc}}{EN_{r,2004}^{pc}}^{0.5}\right) \quad (A2)$$

Municipal water demand (MWD) is determined similarly to industrial water (equation (A3). 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.

$$MWD_t^r = MWD_{2004}^r * \frac{P_t}{P_{2004}} * ED_t^r * TC_t^r \quad (A3)$$

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 Wada et al. (2016) for SSP2. The municipal values are, however, adjusted to fit the projections of municipal water demand from other studies.

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

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-14) 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 (Loulou & Labriet 2008). 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.

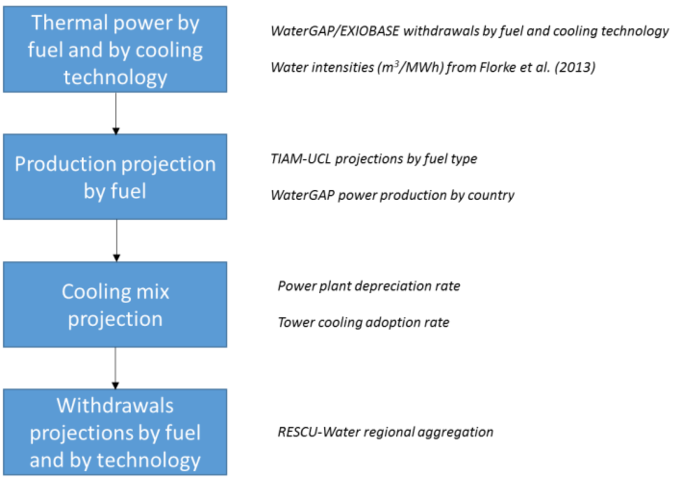


Figure A-14 - Workflow for projecting thermal cooling water demand

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 Flörke et al. (2013) 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: Flörke et al. (2013)

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[8] 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.

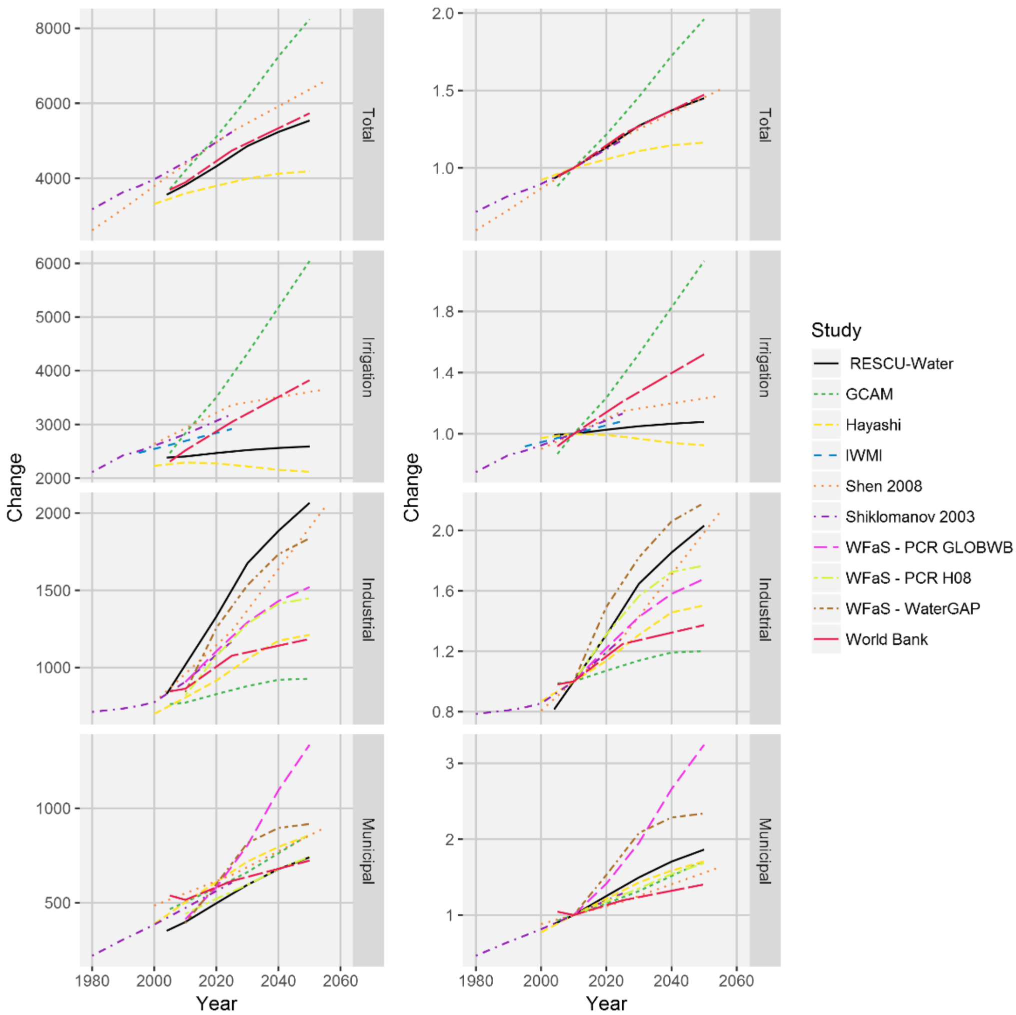
The cooling mix evolution is then determined in the third step. This calculation is done by taking into account that newer power plants are likely to become more water efficient through a gradual adoption of tower-cooling. For each year, power generation by fuel and by cooling type is split into two 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

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

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%).



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

Figure A-15 - Baseline withdrawals compared to other studies

Studies: RESCU-Water (this study), GCAM (Hejazi et al. 2014), Hayashi (Hayashi et al. 2013), IWMI (de Fraiture et al. 2010), Shen 2008 (Shen et al. 2008), Shiklomanov 2003 (Shiklomanov & Balonishnikova 2003), WFaS PCR GLOBWB, H08, WaterGAP in (Wada et al. 2016), World Bank (World Bank 2016)

These RESCU-Water total withdrawal values are comparable to other global projections. Figure A-15A 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[9] are also included in Figure A-15B. 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).

Irrigation withdrawals for the RESCU-Water baseline are found at the lower end of projections. Industrial withdrawals (reported Figure A-15B as the sum of industrial supply and thermal cooling for comparative reasons[10]) 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.

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 (Table A-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-16.

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.

[9] 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

[10] 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)

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.

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

RESCU-Water region	Total withdrawals (km^3)		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%

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 Wada et al. (2016) 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[11] 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

[11] Again, industrial withdrawals in Wada et al. (2016) include thermal cooling values. The comparison with RESCU-Water is made accordingly.

RESCU-Water values are lower than WaterGAP and PCR-GLOBWB but higher than H08. The agreement of the RESCU 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.

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-17B). 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-17C) despite the growth in electricity output coming mainly from tower-cooled power plants (Figure A-17D).

Figure A-16 - Regional withdrawals 2004 and 2050 by use category (in km3)

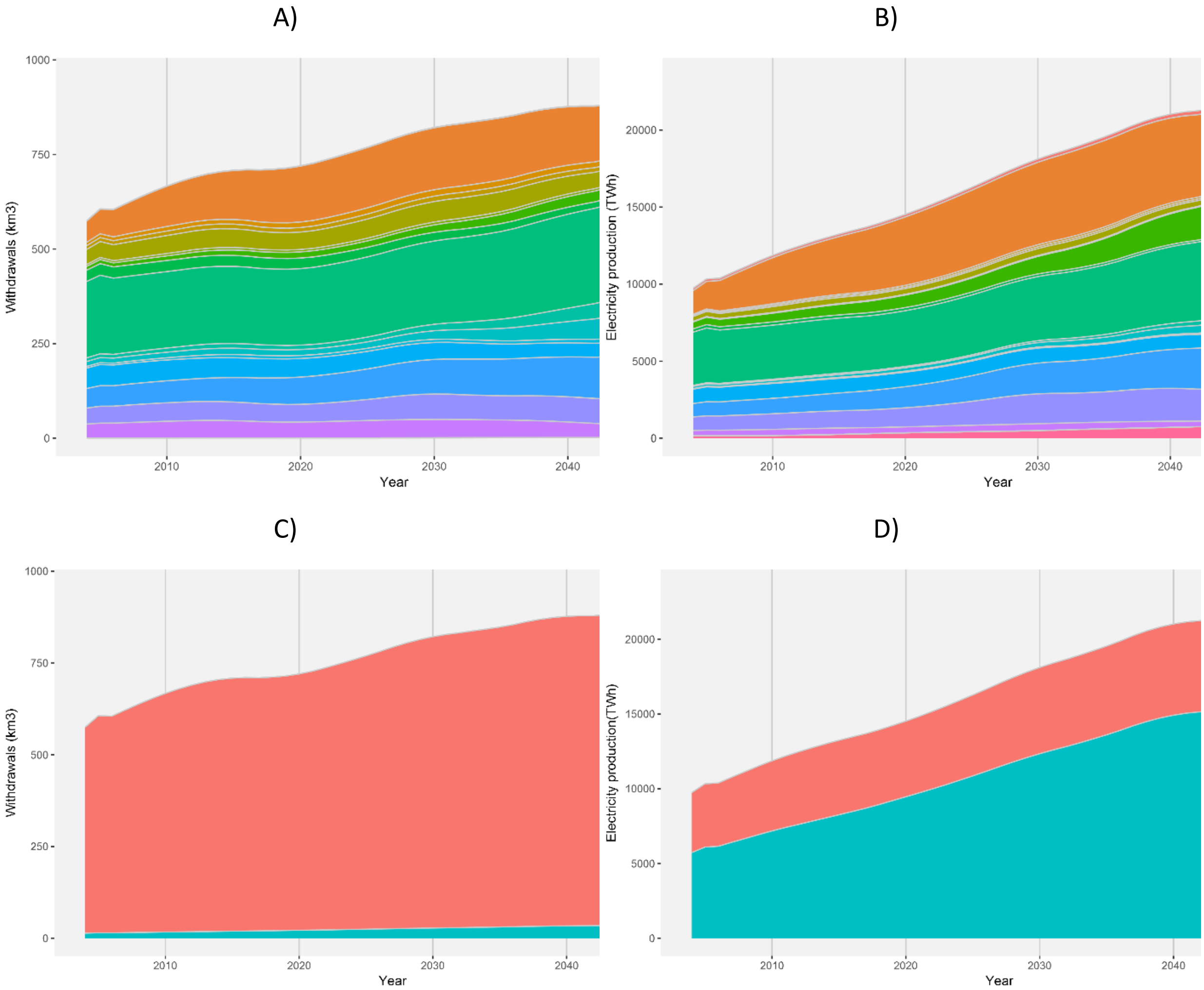


Figure A-17 - Thermal withdrawals and electricity production by region and by cooling method