



Long-term water demand for electricity, industry and households



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ABSTRACT

Better water demand projections are needed in order to better assess water scarcity. The focus in this paper is on non-agricultural water demand, as this is the fastest-growing and least well-modelled demand component. We describe an end use-oriented model for future water demand in the electricity, industry and municipal sectors, with several new features. In the electricity sector, effects of thermal efficiency improvements on water demand are incorporated in our model. In the industry and municipal sectors, we separately estimate potential water efficiency improvements for withdrawal and consumption, so that consumption is no longer a simple fraction of withdrawal. We develop three scenarios for 26 regions and the period 1971–2100. The Medium and High scenarios project increasing global withdrawal (1930–2876 km³/yr) and consumption (537–694 km³/yr) in 2100, with especially dramatic increases in developing regions. Also, an alternative future is presented, with high standards of living and much lower water withdrawal (1010 km³/yr) and consumption (236 km³/yr). Aggressive efficiency measures can reduce baseline withdrawal and consumption in 2100 by 60% relative to zero efficiency gains.

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1. Introduction

Several environmental assessments have concluded that a key environmental problem in the next decades could be increasing water scarcity (OECD, 2012), which has been indicated as a threat to ecosystems (UNEP, 2012), food production and rural livelihoods (Biemans, 2012; FAO, 2008) and electricity production (IEA, 2012; World Water Assessment Programme and UN-Water, 2014). Water scarcity may also hamper industrial development and economic growth (World Economic Forum, 2011; World Water Assessment Programme, 2009) and worsen living conditions for the urban poor. Water scarcity is caused by rapidly increasing water use (due to rapidly increasing population size and economic activity) and changing precipitation and evaporation patterns (due to climate change and land use). For effective response strategies, it is important to understand how water demand and supply may develop in the future. Unfortunately, models of long-term water demand are still in their infancy. Water withdrawal projections

made before 1990 substantially overestimated the ensuing global water withdrawal, whereas later models consistently underestimated global withdrawal while overestimating for some regions (Amarasinghe and Smakhtin, 2014).

The term ‘demand’ refers to the volume that is desired, whereas ‘use’ refers to the demand that can actually be satisfied when taking into account supply constraints. The model and projections discussed in this paper focus on demand only, as we do not confront demand with a model of future supply constraints (see Supplementary Table S1 for definitions of key concepts). Water demand has two important components: withdrawal (total water intake) and consumption (water made unavailable for other purposes, e.g. due to evaporation). Any water that has not been ‘consumed’ is by definition returned to the freshwater supply. Demand for water originates from various economic sectors. Agriculture has been dominant, with 67% of global water withdrawal and 89% of consumption in the year 2000 (UNEP, 2007). In this paper, we focus on the electricity, industry and municipal sectors as, so far, the water demand for these sectors has been less well-represented in integrated assessment models and because their demand is growing faster than demand from agriculture (OECD, 2012; UNEP, 2012). The non-agricultural sectors may also create new challenges for water allocation, since they place a higher economic value on water as compared to the

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agricultural sector (leading possibly to increased scarcity for the agricultural sector).

To understand future water demand, we link demand to relevant sectoral drivers in terms of activity levels, structural factors and potential efficiency improvements. Water use for electricity generation and other industrial activities are often lumped together in databases (FAO, 2013) and models (Hanasaki et al., 2013; Hayashi et al., 2013; Wada et al., 2011). However, since water demand in these sectors is used for different purposes, it is more appropriate to deal with them separately. The key questions we address in this paper are:

1. How could water demand in the electricity, industry and municipal sector develop under different scenarios?
2. What role may efficiency play in reducing water demand?

In order to address these questions, we propose a new end-use-oriented water demand model. This model improves upon existing models in accounting for efficiency improvements both in water end-uses and in terms of driving forces. We apply the model to scenarios along the storylines of the recently introduced shared socioeconomic pathways (SSPs) (O'Neill et al., 2014). These scenarios are internally consistent sets of assumptions about future economic, demographic and technological developments. Besides these scenarios, we investigate the potential impact of efficiency improvements on model outcomes. The model is part of the integrated assessment model IMAGE (Integrated Model to Assess the Global Environment). It can be combined with models of water supply and agricultural water demand, such as LPJmL (Bondeau et al., 2007) or PCR-GLOBWB (Van Beek and Bierkens, 2009), to calculate overall water scarcity (PBL, 2014).

2. Methods

Non-agricultural water demand can be subdivided by economic sector in several ways. We distinguish the *electricity*, *industry* (manufacturing, mining) and *municipal* sectors, because these constitute the large contributors to non-agricultural demand, and are each influenced by different driving forces (i.e. excess heat, industrial production and population size).

Our concept of future demand is 'the amount that would be used in the absence of supply constraints' (Supplementary Table S1). Since historical demand is unknown, we estimate future demand based on historical use (although historical use could be lower than demand due to supply limitations in dry years).

Since water consumption is less easily measured than withdrawal, most data sources do not report water consumption. AQUASTAT (FAO, 2013) only provides good estimates for water consumption for the municipal sector and only for the last decade, estimated as the difference between water withdrawal and collected wastewater. Since even these data are incomplete, we model industrial and municipal water consumption as a fraction of withdrawal, as is commonly done in other studies (Flörke et al., 2013; Shaffer and Runkle, 2007). Whereas this fraction remains fixed or changes very little in previous studies, our model allows for converging (or possibly diverging) withdrawal and consumption based on future efficiency improvements. Industrial withdrawal and consumption efficiency may improve due to recycling and energy/process efficiency respectively (Section 2.5.2). Municipal withdrawal and consumption efficiency depend on widespread acceptance of water-efficient technologies for each use function (e.g. baths, toilets, garden watering) (Section 2.5.3).

In all three sectors, we model future water withdrawal as the product of an activity level, the water intensity of that activity, and efficiency factors (see Fig. 1 for conceptual models). The spatial

resolution of the model is the 26 IMAGE regions. The time dimension ranges from 1971 to 2100, with a yearly time step. Seasonal effects are not considered explicitly. The focus on yearly totals enables a clearer analysis of long-term trends.

2.1. Data sources

Historical water use is based on AQUASTAT and, for the industry sector, partly on the WaterGAP model (Flörke et al., 2013). From the World Development Indicators (World Bank, 2013), population and Industry Value Added (IVA) are used for aggregating from countries to 26 IMAGE regions. Water use intensities for the electricity sector are based on Macknick et al. (2011) and fuel-to-electricity conversion efficiencies are based on TIMER, the energy sub-model of IMAGE (PBL, 2014). Historical population size, gross domestic product (GDP) per capita and IVA at the regional level were obtained from PBL (2014). Future projections are based on scenarios developed by the TIMER team, with additional assumptions for the mix of power plant cooling systems based on Davies et al. (2013) and NETL (2011). Future water efficiency improvements for the electricity sector are based on Feeley et al. (2008). For the municipal sector they are based on current U.S. water end uses (Mayer et al., 1999) and utilization of highly efficient technologies (De 12 Ambachten, n.d.; Gleick et al., 2009; Orbital Systems, n.d.; Yanko Design, n.d.). Future efficiency in industry is estimated from historical improvement rates (David, 1987; Eurostat, n.d.) and the remaining gap between withdrawal and consumption (Flörke et al., 2013).

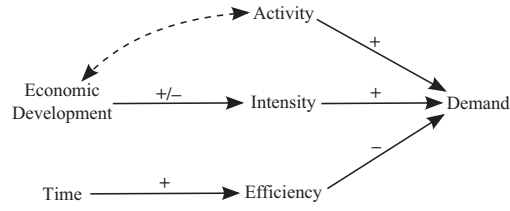
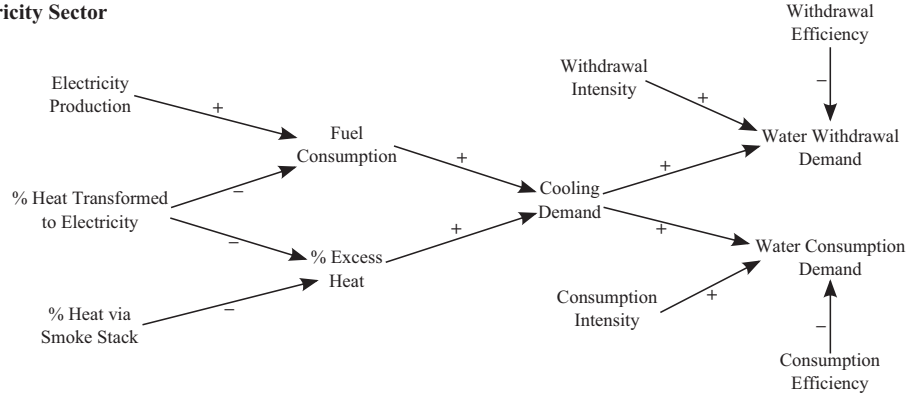
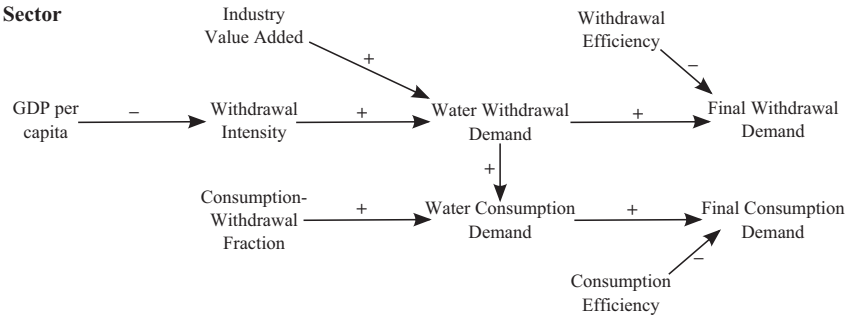
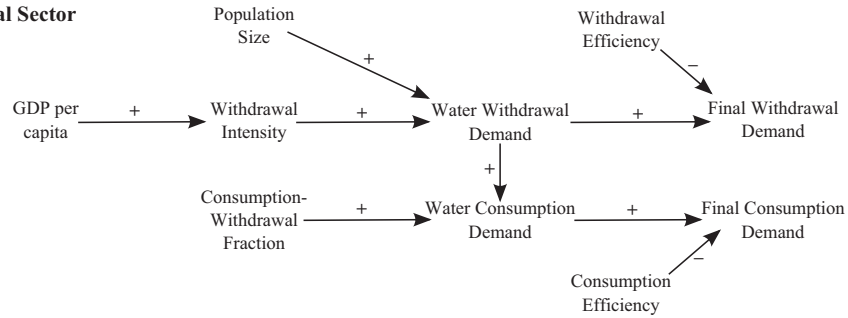
2.2. Electricity sub-model

In electricity generation, water is used for cooling thermoelectric power plants, including concentrated solar power (CSP). Wind turbines and photovoltaic cells are assumed to operate without any water, whereas geothermal power is excluded due to its small scale. The water demand for cooling depends on the waste heat of power plants (and thus on the fuel and power plant type), and on the cooling type and efficiency. Once-through cooling conducts large volumes of (sea) water past a heat exchanger and then returns almost all water. Wet tower cooling uses evaporation of freshwater. Dry towers use virtually no water, since air flows along the heat exchanger. Pond cooling is a hybrid form between once-through and wet tower cooling, used mainly in the United States. The current tendency is to avoid once-through cooling and use more wet tower cooling, partly due to decreasing surface water availability, higher water temperatures, and stricter discharge temperature regulations. This trend is expected to continue worldwide in the coming decades (Davies et al., 2013).

In most existing models, the driver is electricity production (Davies et al., 2013; Flörke et al., 2013). However, since cooling water demand is directly linked to the amount of excess heat, we use the latter as driver, calculated from fuel input and an energy balance. Fuel use is influenced by population size and economic activity, in TIMER. The equation for electricity sector water withdrawal is

$$W_r^E(t) = \sum_{p,c} F_{p,r}(t) \cdot (1 - \nu - e_{p,r}) \cdot I_{p,c} \cdot M_{p,c,r}(t) \cdot E_c^E(t) \quad (1)$$

where W_r^E is water withdrawal (m^3/yr), the subscript r is for region, p for plant/fuel type, c for cooling system, and t for time dependence. Excess heat, the amount of energy (GJ/yr) that needs to be cooled away, is calculated from fuel use $F_{p,r}$ (GJ/yr), the fraction of energy input that is vented through the smoke stack ν ($\nu = 0$ for CSP and nuclear), and thermal efficiency $e_{p,r}$. We use scenarios describing fuel use and thermal efficiency from TIMER (PBL, 2014). Here, power plant types compete for market share

General Conceptual Model**Electricity Sector****Industry Sector****Municipal Sector****Fig. 1.** Conceptual model for each sector.

mostly based on their operational costs. Plants are assumed to become more efficient over time as described in Van Vuuren (2007). Water intensity $e_{p,r}$ (m^3/GJ) is the water volume used per gigajoule excess heat (Supplementary Table S2). It is held constant across regions and time at the levels of the year 2000, which are back-calculated from USA data (Macknick et al., 2011) and fuel efficiencies from TIMER. The cooling system market shares $M_{p,c,r}$ add up to 1 for each combination of plant/fuel type p and region r , and are specified in Section 2.5. Together, $I_{p,c}$ and $M_{p,c,r}$ represent structural changes in the electricity sector. E_c^E is a scenario-dependent water efficiency factor (between 0 and 1), included because considerable water savings are possible in wet tower cooling (Feeley et al., 2008).

The exact same formula applies to consumption C_r^E (in m^3/yr), but with different intensities ($I_{p,r}$) (Macknick et al., 2011) and different water efficiency factors (E_c^E)

2.3. Industry sub-model

The industry sub-model covers all industrial activities that have their own water supply, excluding electricity generation. Small businesses in cities are part of the municipal sub-model, being supplied by the municipal water system. Examples of industrial activities that are often self-supplied are the production of chemicals, paper and paper board, pig iron, fabrics, crude steel, sugar, beer and cement (Vassolo and Döll, 2005). Our approach groups all such industrial activities together.

As driving force we use industry value added (IVA) in inflation and purchasing power parity corrected 2005 dollars. We write the unit as IVA\$, to avoid confusion with GDP\$. We use IVA because it covers a wide range of industrial processes and is reported annually for almost all countries (World Bank, 2013). Whereas a model with specific water-intensive industrial activities would be

more process-based, it would also require assumptions on long-term production volumes and water intensities for each industrial activity in every region.

Regarding water intensity, cross-temporal and cross-regional data suggest that as GDP per capita increases, many countries follow a pattern of decreasing water withdrawal per IVA\$. This can be understood by the influence of two factors: structural change and efficiency (Fig. 1). First, structural change in the economy will influence water use, since industrial activities vary widely in the volume of water needed to add one dollar of value. For example, when a country producing mostly basic metals expands its less water-intensive activities (such as textiles or food processing), overall industrial water intensity (in $\text{m}^3/\text{IVA}\$$) decreases. As economies develop, they experience an increase in industrial activities that are more complex or higher up the value chain, and thus water use is expected to grow less rapidly than IVA. There are substantial regional differences in historical freshwater abundance, economic development pathways and water use patterns, resulting in some regions with very high industrial water intensities (Kazakhstan and Ukraine regions, India) and others with very low intensities (Middle East, Oceania, Japan). Second, water efficiency improvements reduce water demand. Water withdrawal per tonne production has been reduced as fast as 5% per year in Europe, during the period 2002–2011, for various industries (Eurostat, n.d.). Reductions in water discharge intensity (withdrawal minus consumption) ranged from 2.7% per year for steel processing to 5.7% per year for chemicals in the USA during the period 1954–1983 (David, 1987). These substantial year-on-year efficiency improvements were partly motivated by new environmental regulations and fees for water intake and/or discharge, so the average annual efficiency improvement over the whole historical period should be lower. For developing countries (Gleick, 2000) cites examples ranging from 42 to 62% efficiency improvement within a few years of focused effort at single industrial plants. Clearly, average efficiency improvements in any given year are considerably lower. For instance, energy efficiency in industry has improved at much lower rates around 0–1.5% per year over longer time periods (Schipper and Meyers, 1992). If the 42–62% improvements had been achieved gradually between 1971 and 2011, the annual efficiency improvement would be 1.35–2.39%. Since we lack more consistent data sources, we assume efficiency improvements of 2.5% per year during 1971–2011 for industrial water withdrawal in both developing and developed regions.

Our equation for industrial water withdrawal is:

$$W_r^I(t) = V_r(t) \cdot a \cdot G_r(t)^b \cdot R_r^I \cdot E_r^I(t) \quad (2)$$

where W_r^I is industrial withdrawal volume (m^3/yr), in region r at time t . V_r represents the economic driving force, total industry value added ($\text{IVA}\$/\text{yr}$), and is specified by scenarios. The global withdrawal intensity ($\text{m}^3/\text{IVA}\$$) follows the power law $a \cdot G_r(t)^b$, where G_r ($\text{GDP}\$ \text{ capita}^{-1} \text{ yr}^{-1}$) is used as proxy for the development and structure of a region's economy. Withdrawal intensities were obtained by aggregating AQUASTAT withdrawal data to IMAGE regions, subtracting modelled withdrawal for electricity, and dividing by historical IVA (from IMAGE). For regions with negative values or insufficient data, we substituted 'manufacturing' withdrawal from WaterGAP (Supplementary Table S3). We then adjusted for historical efficiency improvements to isolate the structural change effect. Linear least squares calibration (Fig. 2) resulted in $a = 3.57$ and $b = -0.564$. We assume each region follows the global trend, starting from their latest known intensity levels, using region-factor R_r^I . Alternative approaches are discussed in the Supplementary material. Finally, we multiply by an efficiency factor E_r^I (between 0 and 1) based on observed trends (for the historical period) and differentiated by scenario (for the future).

Consumption is calculated with the 2011 consumption-withdrawal fractions from WaterGAP (Supplementary Table S3). However, future withdrawal and consumption may converge due to different efficiency improvements (Section 2.5).

2.4. Municipal sub-model

The municipal sub-model covers water demand in households (indoor and outdoor), but also in the service sector, small businesses and local institutions, because currently available global data (FAO, 2013; Gleick et al., 2009) do not separate household water use from other municipal uses. We use population size as the driver and base our water efficiency estimates on households, because these represent the majority of municipal water withdrawal (e.g. 83% in the USA (United States Environmental Protection Agency, 2014)) and because we expect the size and behaviour of urban businesses and institutions to reflect that of the general population. In Eq. (3), we again model water demand as a function of activity, intensity (structural changes) and efficiency, with one factor for regional deviations from the global model:

$$W_r^M(t) = P_r(t) \cdot \frac{c}{1 + e^{(m - \ln(G_r(t)))/s}} \cdot R_r^M \cdot E_r^M(t) \quad (3)$$

where W_r is total municipal water withdrawal (m^3/yr) and P_r denotes population size. Global withdrawal intensity (m^3/capita) follows a logistic growth function of log income G_r ($\text{GDP}\$ \text{ capita}^{-1} \text{ yr}^{-1}$) with midpoint m , maximum intensity c , and horizontal scale parameter s (Fig. 2). Withdrawal intensities were obtained by aggregating AQUASTAT municipal withdrawal to IMAGE regions (interpolating for missing years and correcting for missing data using population size (World Bank, 2013)), then dividing by population from IMAGE and adjusting for estimated historical efficiency improvements. Since missing data still affected the aggregates, from each region we used only the most recent aggregate with the most complete country-level data. Although no minimum volume is required, and we do not adjust for the population fraction that has access to municipal water supply, we found that such elaborations hardly affect the general tendency. Non-linear least squares calibration (Fig. 2) yielded $m = 8.575$ and $s = 0.6985$. To make the calibration procedure work, parameter $c = 143.5 \text{ m}^3/\text{capita}/\text{year}$ (maximum intensity for the global model) was set exogenously as the population-weighted average intensity of regions with GDP/capita above 20,000. R_r^M is the regional factor, accounting for cultural differences (Supplementary Table S4). E_r^M refers to efficiency improvements that do not affect the level of service to end users. Historical annual efficiency improvement was estimated at 1.02% for withdrawal and 0.06% for consumption, based on efficiency improvements in showerheads, toilets, laundry machines and faucets (United States Environmental Protection Agency, 2014), the distribution of water uses in U.S. households (Kindler and Russell, 1984; Postel, 1984), assumed consumption-withdrawal-fractions per end-use (e.g. 0% for toilets), and assumed market penetration rates for technologies.

Consumption is calculated with WaterGAP consumption-withdrawal fractions for the year 2000 (Supplementary Table S4). However, future withdrawal and consumption volumes may converge or possibly diverge, because the efficiency factors are specified separately (Section 2.5).

2.5. Scenario specification

The scenarios describe plausible and internally consistent varieties of future socio-economic systems at the global and regional level (O'Neill et al., 2014; PBL, 2014). The names of our

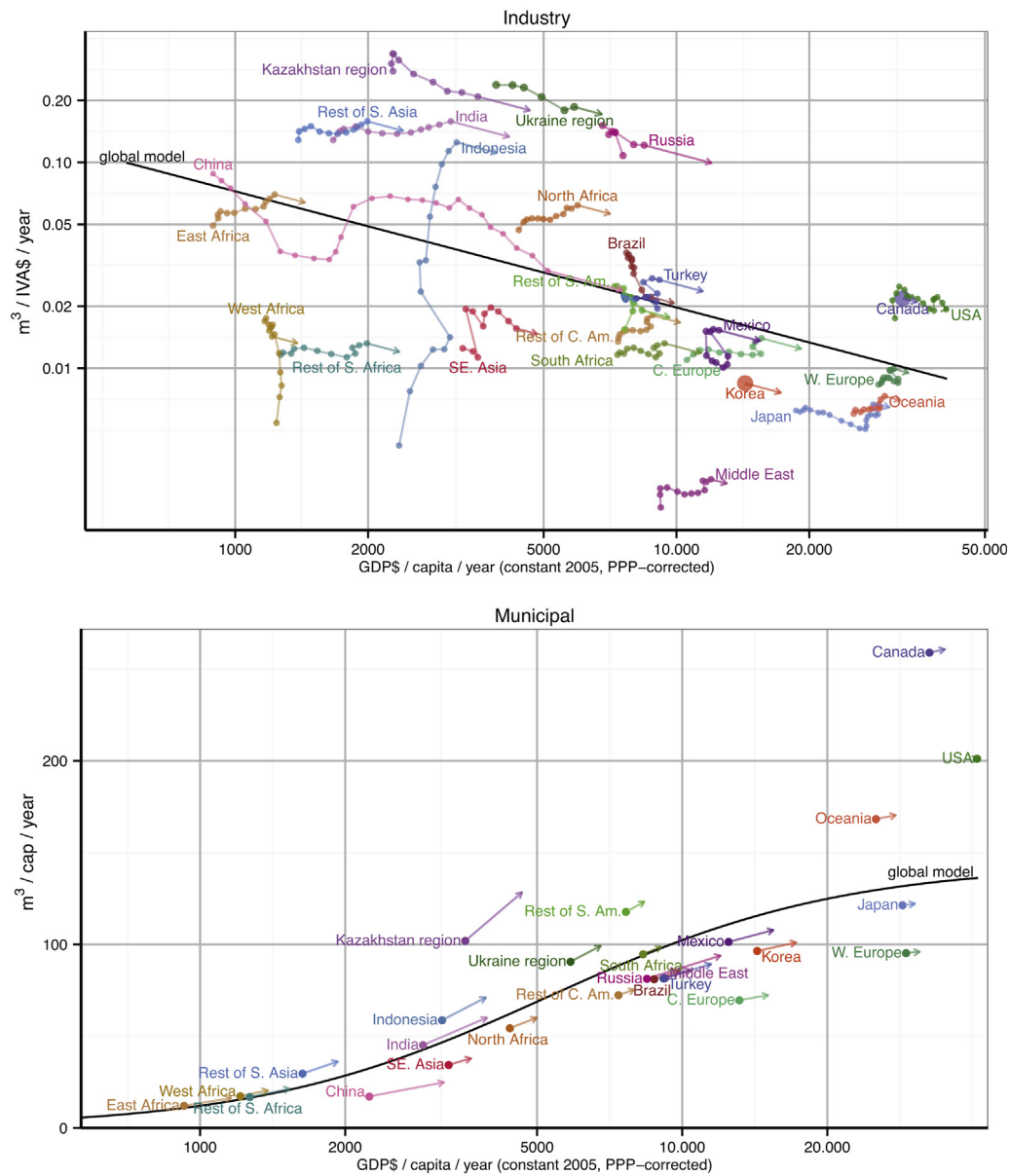


Fig. 2. Industry and municipal structural change. For industry, connected dots are aggregated withdrawal data divided by IVA and corrected for historical efficiency improvement. The black line indicates the global model (power law). For the municipal sector, dots are the latest, most reliable, aggregated withdrawal data divided by population and corrected for historical efficiency improvement. The global model (black) is logistic growth in log income. For both sectors, arrows indicate modelled regional intensities in the five years after the latest data point.

three scenarios (Low, Medium and High) refer to the resource intensity and overall unsustainability of the world. Low represents a world oriented at sustainable development, meeting the challenges of climate change mitigation and adaptation, featuring less inequality and rapid development of environmentally friendly technologies such as renewable energy. By contrast, the High scenario features rapid population growth, slow technological progress, high inequality and reduced international trade and cooperation. Medium is in between the Low and High scenarios on each dimension (Table 1). We use scenario projections for population, income, IVA, electricity fuel input and electricity technologies from the TIMER energy model.

2.5.1. Electricity scenarios

For power plant cooling systems, we assume the High scenario keeps the 2005 cooling system market shares, which are estimated

for each region in a procedure similar to (Davies et al., 2013). In the Low scenario, once-through freshwater cooling systems are gradually replaced with wet tower, dry tower, or sea water cooling, depending on regional geography and climate. We account for the inertia of current installed capacity by adjusting the shares of different cooling technologies linearly between 2005 and 2045. The 2045 market shares were derived as follows. The sea-water share in once-through cooling decreases from 30% to 5% in the USA, and is held constant elsewhere. Dry tower cooling is appropriate for rich, dry countries and replaces wet towers up to 30% market share for all fossil fuel power plants in the Middle East and Oceania. All combined cycle power plants elsewhere use 25% dry tower, 75% wet tower, following scenario 4 in NETL (2011). Nuclear plants in water-scarce regions with abundant coastline (Japan, Korea and Middle East) use once-through cooling only, mostly seawater (Davies et al., 2013). Other coastal regions increase sea-water once-through cooling to

Table 1
Scenario specification.

Scenario	Low	Medium	High
Population growth	Peak around 8.5 billion in 2050	Peak around 9.5 billion in 2070	Around 13 billion in 2100 and increasing
Average income	Increases to 85,000 in 2100	Increases to 60,000 in 2100	Increases to 25,000 in 2100, with larger regional differences
Industry value added	Increases to 92×10^{12} IVA\$ in 2100	Increases to $119 \times 10^{12} \times$ IVA\$ in 2100	Increases to 51×10^{12} IVA\$ in 2100
Electricity production	Peak around 280 EJ/year in 2090	Around 380 EJ/year in 2100 and still increasing	Around 290 EJ/year in 2100 and still increasing
Electricity technologies	More natural gas and wind power (offshore and onshore)	Mostly coal (transitioning to combined cycle), some natural gas, wind, hydropower, nuclear	More conventional coal, less wind
Mix of cooling systems	Full adaptation	50% adaptation everywhere	Unchanged
Wet tower water efficiency	Toward 55.9% (withdrawal) and 50.4% (consumption) less water use in 2040	Half the water savings of the Low scenario	No water savings
Industrial water efficiency	Save 1.05–3.33% per year (withdrawal) and 1% (consumption)	Save 0.55–2.84% per year (withdrawal) and 0.5% (consumption)	Save 0.05–2.35% per year (withdrawal) and 0% (consumption)
Municipal water efficiency	Save 0.73% per year (withdrawal) and 0.85% (consumption)	Save 0.48% per year (withdrawal) and 0.49% (consumption)	Save 0.28% per year (withdrawal) and 0.22% (consumption)

80% for nuclear power plants. For all other technologies and regions, the current shares are carried forward, and any remaining market share is assigned to wet tower cooling. Medium scenario shares are the average of Low and High.

Future water efficiency of wet towers is based on [Feeley et al. \(2008\)](#). For the Low scenario we assume such water savings are achieved worldwide by 2040, with a linear ramp-up from 2015. The Medium scenario achieves half these water savings. Water efficiency remains unchanged in the High scenario and for once-through and pond cooling.

2.5.2. Industry scenarios

There is considerable room for further water savings in industrial processes ([Gleick, 2000](#)). Withdrawal per unit of production is generally reduced by recycling water more times before discharge. Consumption intensity is harder to reduce, since the production process itself is involved. Therefore, we expect the consumption–withdrawal-fraction to increase steadily, as happened in the USA during 1954–1983 ([David, 1987](#)). Since water consumption is partly linked to industrial energy use via evaporative cooling, we assume water efficiency improvements similar to industrial energy efficiency assumptions in TIMER. Assuming the consumption–withdrawal-fraction reaches 75% in 2100, we calculate the implied annual improvement for withdrawal. This means that withdrawal efficiency increases quickly in regions with low consumption–withdrawal-fractions (e.g. USA), whereas it increases very slowly when the consumption–withdrawal-fraction is already high (e.g. North Africa). For most regions, the annual withdrawal efficiency improvements are slightly below the historical trend of 2.5%.

2.5.3. Municipal scenarios

For the municipal sector, various technologies are already available to drastically reduce water use in bathrooms, toilets and gardens. We assume market penetration rates for these technologies in 2100: 75–100% for Low, 50–80% for Medium and 25–60% for the High scenario. The share of end uses in household water use is based on [Mayer et al. \(1999\)](#), and the resulting efficiency gains over 2011–2100 are then annualized. We did not construct separate regional estimates because we lack data regarding the share of outdoor in total municipal use for each region.

3. Results

3.1. Historical model performance

We evaluated model behaviour over the historical period 1971–2011 using regional population size, GDP/capita, IVA, electricity

production and thermal efficiency of power plants from TIMER. Cooling system market shares were held constant at the 2005 values. Assumed historical water efficiency improvement (for withdrawal) was 2.5% for the industry sector, 1.02% for the municipal sector and 0% for the electricity sector (Sections 2.3 and 2.4). Although data for the latest years were used for calibrating the industry and municipal sub-models, the earlier data still provide an independent basis for model evaluation (see [Fig. 3](#)). For industry and electricity (left panel), the model reproduces withdrawal reasonably well for Brazil, China, Japan, Mexico, Turkey and the United States. For three regions, Indonesia, India and South Africa, there are large discrepancies between model and data. AQUASTAT water withdrawal for Indonesia increases very steeply, which could signal underreporting in earlier years, or very rapidly expanding water-intensive, low value-added industrial activities. Trends in IVA, on which our model based, do not show a similar rapid increase. India reports low water withdrawal for 35 years, which seems unlikely given the marked increases in electricity production and IVA during this period. Other literature estimates are substantially higher in 2000 and WaterGAP also assumes steady increases afterwards. Water withdrawal in South Africa decreases by 50% in 10 years, according to AQUASTAT, whereas the Department of Water Affairs and Forestry (DWAF) of South Africa presents higher estimates at 1.78 km³ in 1980 and 1.6 km³ in 1996 ([Eberhardt and Pegram, 2000](#)).

Municipal withdrawal data (right panel) between 1975 and 2010 is reproduced quite well by the model, for each of these regions.

3.2. Scenario projections

Since water scarcity is more a regional than a global issue, we analyse water demand at the regional level. Common patterns appear among the 26 regions, so we categorize the regions and present one region from each category in [Fig. 4](#). The categorization is based primarily on the projected total withdrawal in the Medium scenario, and secondly on any sector being dominant. The group of “declining regions” (USA, Canada, Western Europe, Central Europe, Ukraine region, Russia, Korea and Japan) is characterized by declining total water withdrawal (mostly electricity and industry, but with major reductions in the municipal sector in Japan and Korea). A group of “peaking regions” (Kazakhstan region, India, China, Indonesia and South East Asia) features rapidly increasing water withdrawal, peaking before or around 2050, and stabilizing or declining afterwards. A third group is labelled “population-dominated regions” (Mexico, Rest of Central America, Brazil, Rest of South America, South Africa (the country), Turkey, Middle East

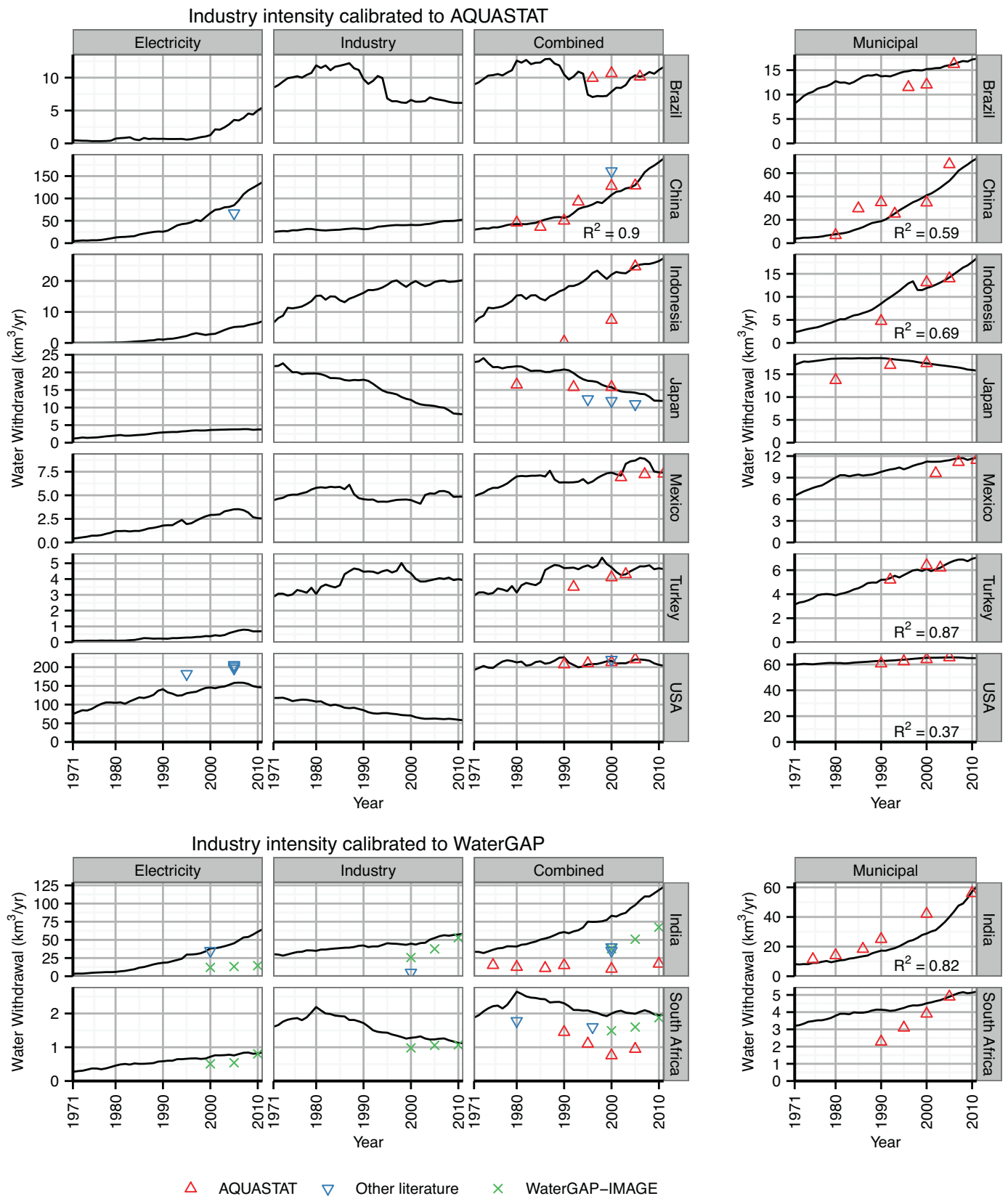


Fig. 3. Historical model performance. Modelled withdrawal (lines) is compared with data for the industry and electricity sectors (left) and municipal (right). Data are from AQUASTAT (red triangles), various others listed in [Davies et al. \(2013\)](#) and [Eberhardt and Pegram \(2000\)](#) (blue inverted triangles), and WaterGAP model output modified by IMAGE (green crosses). We show nine regions that correspond to single countries. The coefficient of determination (pertaining to AQUASTAT only) is shown when positive. Electricity sector withdrawal was not calibrated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

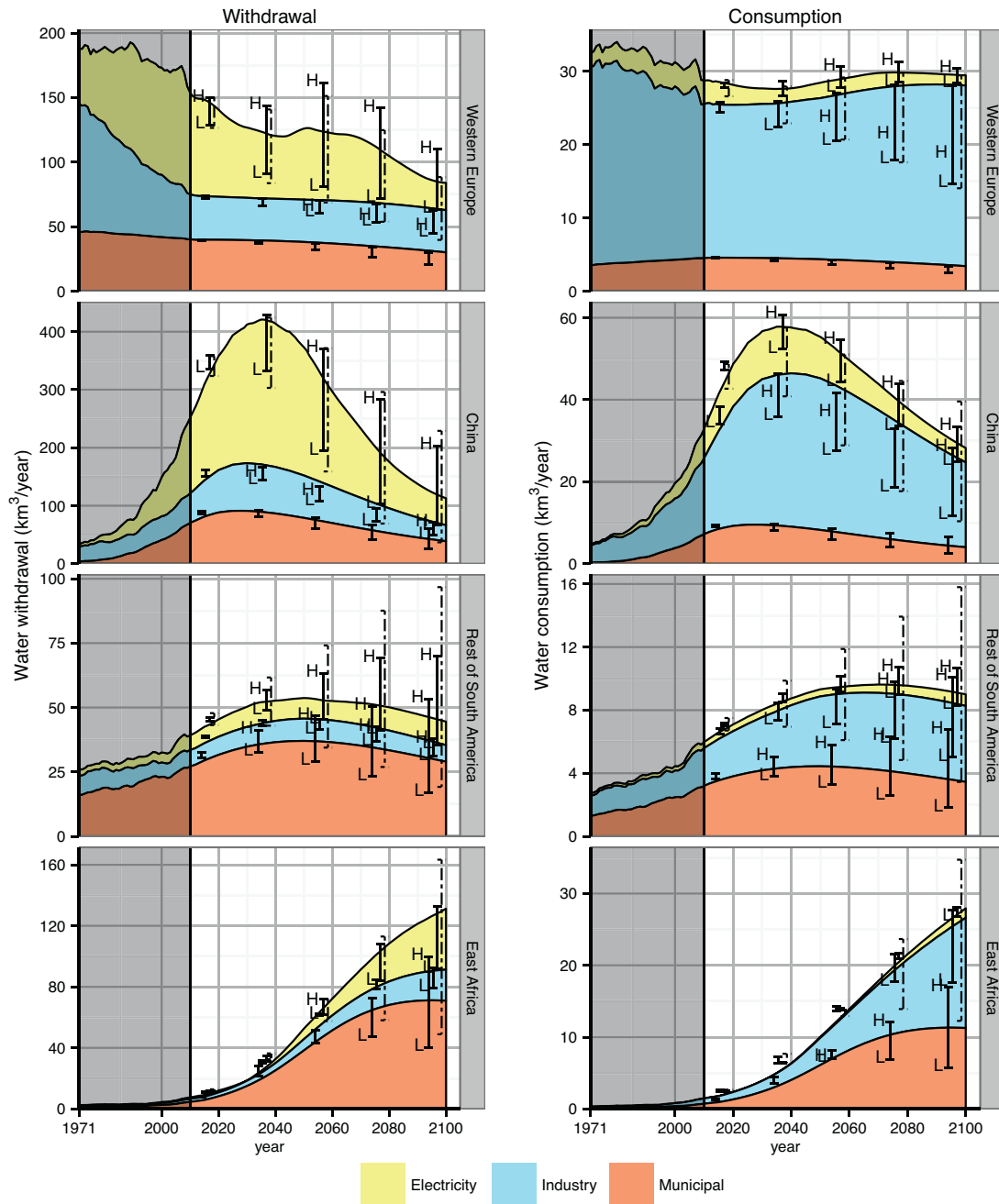


Fig. 4. Projected withdrawal and consumption for the Medium scenario. The vertical bars indicate the range of outcomes under the three scenarios (L/H referring to the Low/High scenarios). We present one region from each category.

and Oceania), since their water withdrawal is dominated by the municipal sector and increases modestly. The fourth and final group, “later developing regions” (West Africa, East Africa, Rest of Southern Africa and Rest of Southern Asia) exhibits exponential growth in withdrawal volumes (starting from a very low level), originating from the municipal and electricity sectors, with almost no contribution from industry. North Africa falls outside these categories: withdrawal more than doubles to reach a peak near 2100 and each sector contributes equally.

In Fig. 4 (left panel), total water withdrawal in Western Europe roughly halves over the course of the century, and most of the scenario variance occurs in the electricity sector. In China, electricity generation is already the largest sector, and water withdrawal peaks around 2035 at almost twice the amount in

2010. The Low scenario has a lower peak in China, whereas the High scenario features the same peak demand but a less rapid decline afterwards. For the region “Rest of South America” (excluding Brazil), water withdrawal increases less rapidly and the municipal sector dominates. However, a very wide range of outcomes is possible, from an early decline (Low scenario) to ever-increasing demand (High scenario). East Africa’s withdrawal starts from extremely low values, but grows exponentially until around 2050. At this point, withdrawal demand could stabilize (Low scenario), or could triple before 2100 (High).

Consumption projections (Fig. 4, right panel) are related to withdrawal by initial consumption–withdrawal-fractions for the industry and municipal sectors, but different future efficiency improvements allow the consumption–withdrawal-fractions to

change over time. In Western Europe, projected water consumption is dominated by industry and remains roughly constant in the Medium scenario. Interestingly, consumption steadily declines both in the Low and High scenarios, due to efficiency improvements (Low) and slower growth of IVA (High). For China, Rest of South America, and East Africa, consumption roughly follows the same pattern over time as withdrawal, but the dominant sector is no longer electricity but industry.

3.3. Efficiency effects

Both socio-economic drivers and efficiency factors vary among the Low, Medium and High scenarios, so here we isolate the effect of efficiency assumptions. Population, GDP per capita, IVA, electricity production, and the mix of power plants and cooling systems follow the Medium scenario. Three cases are compared: (1) no efficiency improvements after 2000, (2) Medium thermal efficiency improvements in power plants, but no improvement in water end-use efficiencies, and (3) Medium thermal efficiency and maximum water end-use efficiency in every sector.

Within the electricity sector (Fig. 5, top row), energy efficiency improvements in power plants are able to reduce global water withdrawal (54%) and consumption (63%). Water efficiency in wet tower cooling systems may reduce the remaining water consumption by 40% for the global electricity sector. However, these measures have little impact on withdrawal, since most withdrawal originates from once-through cooling, not wet towers. When water demand from all sectors is combined (bottom row), the impact of energy efficiency is less pronounced. Long-term non-agricultural withdrawal and consumption are highly influenced by industrial and municipal efficiency assumptions. We constructed a plausible range for these efficiency improvements and now observe a wide range of long-term outcomes, highlighting their significance for future research.

3.4. Comparison to earlier projections

We have compared global water demand projections to baseline projections from the literature. A regional comparison

was impractical due to different region definitions, but the effects of model structure and assumptions are still visible at the global level.

Regarding water withdrawal (Fig. 6, top row), the projections for the municipal sector are close to earlier projections, which also differ little amongst each other because all models use AQUASTAT data and very similar baseline population projections. Still, differences are introduced by each author's conceptualization of future efficiencies and structural changes. In the electricity sector, previous withdrawal projections disagree more, but our Medium projection runs along the middle. The industry withdrawal projections are more downward-sloping than in previous studies, partly due to our annual efficiency improvements (0.55–2.84% for the Medium scenario). There is very little difference between Medium (high IVA and medium efficiency) and High (lower efficiency but also lower IVA). The fourth panel shows the combined electricity and industry sectors, because some previous studies do not separate the two. The 2050 withdrawal projection in the OECD Environmental Outlook (OECD, 2012) is probably too pessimistic, since it is roughly 30% above all the other projections.

For water consumption, we could find few previous projections and almost all are based on the GCAM model. Municipal consumption (bottom left) increases faster than the projection by Shiklomanov (2000), because we include structural change (rich people use more water). In the electricity sector, consumption is substantially lower than Davies et al. (2013) while using the same (median) intensities and similar cooling system market shares. Our model includes the effect of thermal efficiency on water demand, thus lowering both withdrawal and consumption in the electricity sector. Hejazi et al. (2014) is even higher than Davies et al. (2013) because they include evaporation from hydro-electric reservoirs. In the industry sector, their much lower consumption is a fixed fraction of withdrawal, where we use separately evolving efficiency factors. For the combined industry and electricity sectors (rightmost panel), industrial water consumption is dominant. Despite large uncertainties in current industrial consumption-withdrawal-fractions and future efficiency improvements, our projection has an upward trend similar to Shiklomanov (2000) and Hejazi et al., 2014.

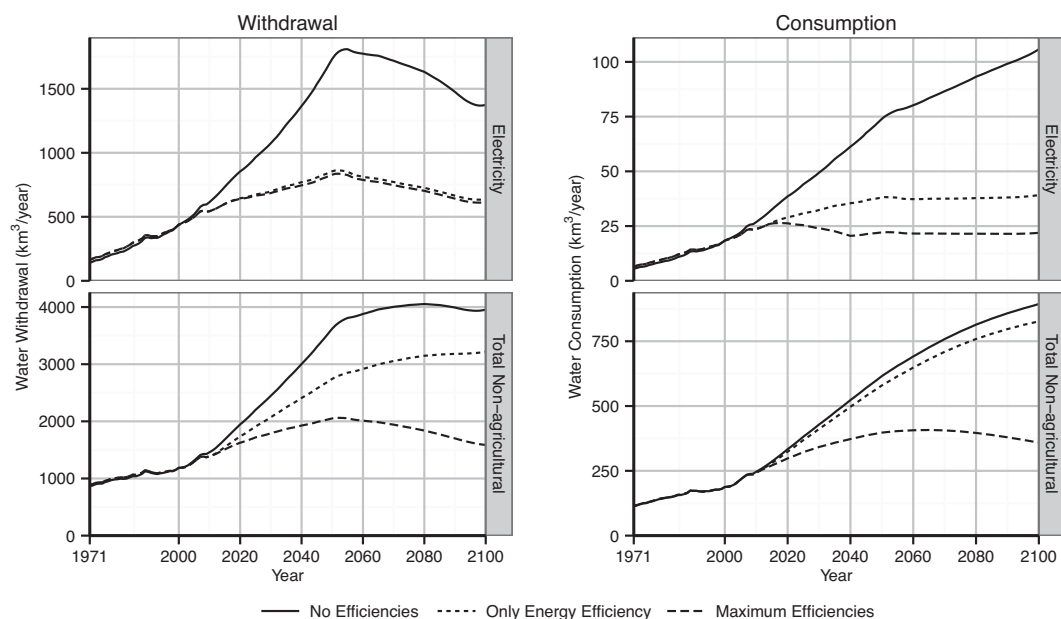


Fig. 5. Influence of efficiency assumptions on withdrawal (left) and consumption (right) in the electricity sector (top) and all sectors combined (bottom). All socio-economic and structural change factors follow the Medium scenario.

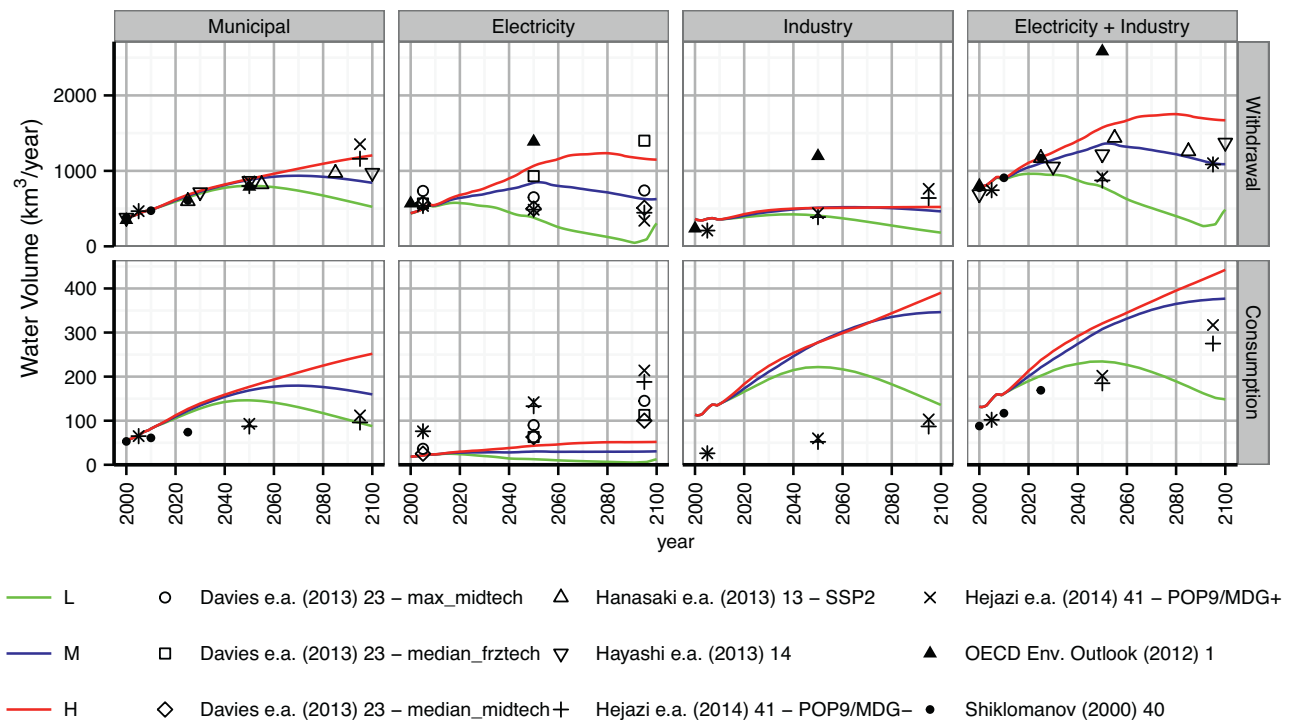


Fig. 6. Comparison with projections from literature. Only 'medium' or 'baseline' projections from each source are shown, and should therefore be compared primarily with our Medium projections (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

4. Discussion

Structural change and efficiency improvement are crucial components of our long-term water demand models, besides activity and intensity. Industrial and municipal structural change was implemented by replacing constant intensities with functions of income. Another key feature of our approach is regional diversity. Each region follows the global model of structural change, but starting from its own intensity level. The electricity sector is modelled in more detail, each region having a different mix of electricity generating technologies, thermal efficiencies, and cooling systems. We now discuss industrial modelling issues, evaporation from hydropower reservoirs, advantages and disadvantages of our approach, and recommendations for future research.

Our model for industrial withdrawal intensity (Fig. 2) captures the global downward trend with rising income, while taking into account regional differences. However, every region is now modelled with a decreasing trend, while the intensity seems to actually still increase in some regions. We explored two alternative models for industrial withdrawal intensity (Supplementary Fig. S1). The alternative approaches are attractive insofar they avoid sharp trend reversals, but they necessitate additional assumptions to constrain the parameters. This makes the height of the intensity peak rather arbitrary, so we consider our simple model to be more useful than these alternatives. Although it is possible to include specific sub-sectors (steel, cement, paper, etc.), we did not do so because (1) sub-sector water intensities vary significantly between regions, and (2) future production volumes would have to be projected for each sub-sector and region.

We made estimates of evaporation from hydro-electric reservoirs as additional context for our demand projections (Supplementary Fig. S2 and Table S6). Global hydropower evaporation is of similar magnitude as water consumption in the electricity, industry and municipal sectors combined, with

important regional differences. This highlights the importance of improving the accuracy and geographical coverage of evaporation intensity estimates.

An advantage of our approach is that it allows for explicit reasoning and experimentation regarding the relative impact of structural change and efficiency improvement. For example, we can investigate to what extent increased household water use per person (due to rising income) can be compensated by increased efficiency (by adopting new technologies). In the electricity sector, assumed thermal efficiency improvements in power plants are able to halve water global withdrawal and consumption, demonstrating the importance of including the energy balance instead of basing water demand on electricity output. In the industry and municipal sectors, our separate assumptions on future efficiency for withdrawal and consumption allow these essentially different water uses to develop differently over time.

Problems were encountered as well. Firstly, there is no global database specifying water withdrawal separately for the electricity and the industry sector. Secondly, water consumption data with broad geographic coverage is lacking for all sectors. For this reason, consumption-withdrawal-fractions have been assumed in previous studies, but their applicability over space and time is uncertain. Municipal consumption-withdrawal fractions in Table S4 could be correlated to outdoor water consumption or leaking municipal infrastructure, but lack of data prevents us to check this at the moment. Thirdly, it was difficult to estimate historical water end-use efficiency improvements, let alone for the future. Since long-term projections are sensitive to annual efficiency improvements, these estimates need better foundations. Finally, it should be noted that the demand model was calibrated on historical use data, which may have been lower than demand due to supply constraints in dry years, resulting in a possible underestimate of actual future demand.

Future research efforts are best focused on water consumption in the municipal, industry and hydropower sectors, because of

their relative size and uncertainty. Withdrawal models are comparatively well-founded, and consumption in the electricity sector is both well-understood and less significant by volume.

The model outcomes (e.g. rapidly increasing water withdrawal) have implications for other parts of Integrated Assessment Modelling, depending on water allocation mechanisms. If resource management policies in developing countries focus on the basic needs of the poor, models of health and demographics should reflect this positive effect. Conversely, in the absence of specific attention to basic needs, growing overall water demand and water scarcity could negatively impact large population segments, both rural and urban. Similarly, rapidly increasing water demand could have detrimental effects on ecosystems (e.g. dried up rivers, disappearing wetlands, inundation by reservoirs), depending on the resource management approach and water allocation mechanisms. Such outcomes should feed back into Integrated Assessment Model components dealing with land use, food production and biodiversity.

Our model may also inform water infrastructure planning and allocation policies, despite the high level of geographic aggregation. For example, the projected peak demand in China, India and other regions raises practical questions: if demand grows so quickly that additional infrastructure cannot keep up, could the resulting temporary scarcity motivate sectors to implement efficiency gains much earlier than projected, significantly reduce the height of the peak, and render part of the initially planned infrastructure redundant?

5. Conclusions

Global water demand is projected to increase dramatically in the Medium and High scenarios. Withdrawal increases to 1930–2876 km³/yr (factor 1.4–2.1 compared to 2010) and consumption to 537–694 km³/yr (factor 2.2–2.9). Water demand grows especially rapidly in developing regions, following exponential growth in some and a sharp peak-and-decline pattern in others. However, a better future is still possible, with high standards of living and much lower water withdrawal (1010 km³/yr, factor 0.73) and consumption (236 km³/yr, factor 0.97).

The realization of a less resource-constrained future depends on effective measures for water recycling and efficiency improvement. Lower water demand in the Low scenario is largely dependent on efficiency improvements, and less on driving forces. Global withdrawal and consumption in 2100 with aggressive efficiency measures are 60% lower than without efficiency gains. For the future to resemble the Low scenario, it is crucial to implement policies and technologies that induce real efficiency improvements in withdrawal (e.g. recycling) and consumption (e.g. air cooling, capturing evaporated water, precision irrigation for gardens).

Thermal efficiency improvements in power plants could significantly reduce global electricity sector water withdrawal (54%) and consumption (63%), irrespective of any water efficiency improvements. The inclusion of this effect in the model is a major improvement upon existing work.

Recent projections reveal considerable uncertainty in future water demand. The sector details allow for new insights. We compared sector model outcomes to each other and to projections in the literature. The global withdrawal projections in the Medium scenario are similar to the literature, despite different model structures and efficiency assumptions. Regarding consumption, we could find few projections for the electricity and municipal sectors, and even less for industry. Our water consumption projections help explore this knowledge gap. Our improved electricity sector water consumption is small compared to previous studies and

other sectors, suggesting that more research effort should be focused on the industry and municipal sectors.

Our model contributes to a better understanding of future water demand, and highlights the most relevant areas for future research. The model incorporates several improvements over existing models. It covers both withdrawal and consumption, in the electricity, industry and municipal sectors, for 26 regions. Its long-term approach includes the effects of thermal efficiency on water demand, and its water efficiency factors allow withdrawal and consumption to converge or possibly diverge as appropriate. However, much work is still to be done in data collection. Continued improvement of models and projections is highly dependent on representative data regarding water consumption (as opposed to withdrawal), historical efficiency improvements, and future efficiency improvement potential, especially in the industry and municipal sectors.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.envsci.2015.09.005>.

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