博士論文

Valuing Water Use at Different Sectors with Considering Socio-Economic Development: Global Scale Assessment

（経済開発水準を考慮した複数セクターにおける水利用価値の全球評価に関する研究）

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Abstract

Water plays an essential role in our economic and social activities. Demographic and climatic changes will increase the pressure on water resources in the future. Therefore it is crucial for Managers, whether in the government or private sectors, to make the right decisions on water allocation. Nowadays, many countries are finding that supply-side solutions alone are not enough to overcome to meet ever-increasing demand; thus, other solutions, such as demand management, are being addressed to overcome insufficient available water.

Water allocates between different sectors and users based on the economic improvement in hydro-economic models. Considering the economic value of water is essential for water planners and managers for water allocation. Also, this kind of estimation enables them to find the costs of water scarcity by estimating the economic benefit of water use in different sectors and calculating the missing amount of water that can't meet demand as an unrealized economic value. With understanding water value in various sectors, a policymaker can mitigate the financial costs of water scarcity by managing the available water in the right way. Maximize the economic benefits of the allocated water can help reduce the costs of future water scarcity under global changes in the world.

The aim of the current framework is how much benefit we can gain from using the unit amount of water in each sector (Irrigation, domestic, and industry). The present work focuses on the demand side of water scarcity assessment.

In the agriculture sector, the shadow price of water as an economic benefit of agriculture water uses for four major crops; maize, rice, soy, and wheat is calculated on a global scale from 1980 to 2010 over grid cells. Since water withdrawal in agriculture is for irrigation proposes, therefore this assessment estimates the shadow price of irrigation water by applying the yield comparison method. This work defines the shadow price as a potential marginal added value by irrigation. The result shows that in terms of global annual average, rice has the highest, and wheat and rice have the lowest shadow price with more than five times difference. Shadow price varies region by region and year by year for all crops.

Estimation of industry water quantity assessment is carried out by following the H08 methodology, and the economic value of the industrial sector on the global scale is estimated based on comparison with desalination technology as the most energy-intense technology of water production. The result shows that IWW (km^3/year) is increased 1.5 times, and it reaches almost 913 km^3 in 2010 compared to nearly 610 km^3 in 1980, although industrial water intensity (m^3/MWh/year) decreases, and it halved during the same time as expected, industrialized countries withdraw more water than developing countries, although in Europe and North America IWW declines after 1990 and 2000 respectively as a result of efficiency growth. The expansion of Asia IWW during time is substantial. The global average of IWW economic value is increased more than 1.5 times, and from almost 1.1 to 1.7 (USD/m^3) for 30 years. The total global IWW value is increased more than 2.3 times, with the average annual growth rate of 4.4%, and it reaches almost 1537 billion USD in 2010 compared to 660 billion USD in 1980. As an application of the industrial sector, we assess the impact of hydropower and renewable energy on IWW economic value. Our result shows that with applying hydropower and renewable energy, economic value is increased by 13% and 1% from 1980 to 2010, respectively.

Domestic water withdrawal is estimated on the grid. We construct both domestic water withdrawal (DWW) and domestic water intensity on the grid level globally from1980 to 2010. DWW is increased 2.3 times from 201 to 469 km^3 between 1980 and 2010, with an annual growth rate of 4.4%. The highest growth rate is captured in Asia and South America. Our result shows that in 1990, 1.43 billion people suffered to access basic human required amount, although this number is decreasing to almost 660 million in 2010. The global average economic value of domestic water use is just increased by 3% from 5278 to 5448 \$yr-1yr-1 with a 0.1%yr-1 growth rate from 1980 to 2010. Oceania and High-income countries have the highest and Asia, and low-income countries have the lowest economic value of domestic water use, since the economic value in Africa and Asia as continental scale, and low and lower middle income countries as income category, is smaller than the global average value.

The economic value of the domestic sector is far above the industry and agriculture sector, and agriculture water value is minimum (agriculture =0.1 USD/m^3, IWW = 1.3 USD/m^3 and DWW = 124.7 USD/m^3 for long term average). Among DWW components, the first par has the highest (330 (USD/m^3) for long term average), and other parts value is less than 10 (USD/m^3) in terms of 30 years average. IWW economic value is less than the 2nd and 3rd part of DWW; also, the economic values of agriculture products are meager in comparison to IWW and DWW. Within countries, in general, developed countries have the highest value. Human activities in all water sectors make almost 30 trillion benefits globally in 2010, although this value is still 2.3 times less than the global GDP in 2010, it shows the importance of water for human life. Total economic benefit increases 1.6 times for 30 years.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 CURRENT WATER RESOURCE SITUATION AND PROBLEMS

Water scarcity is a critical global issue. Humans and other organisms on the Earth need water for their life, therefore ensuring about enough supplies of water is very important for humans (Oki and Kanae, 2006). Although there is a lot of water on the Earth, only 2.5% of that significant amount is freshwater, and since most of the freshwater is stored as glaciers or deep groundwater, only a small portion that 2.5% freshwater is easily accessible (Oki and Kanae, 2006).

On the one hand, Climate change and global warming, and on the other hand, increasing population and consumption have affected this limited water recourses in the world. Climate change causes drought in some regions and wets in others. That means that these vital resources are highly vulnerable (IPCC WGII AR5, 2012). People need to access water, but recent investigations mention that the water and sanitation crisis is one of the biggest killers of children under five years old worldwide. It is estimated that 1800 children under five years old die every day, and it is more than 600,000 children die every year because of water sanitation and hygiene and diarrhoeal (UNICEF, 2013).

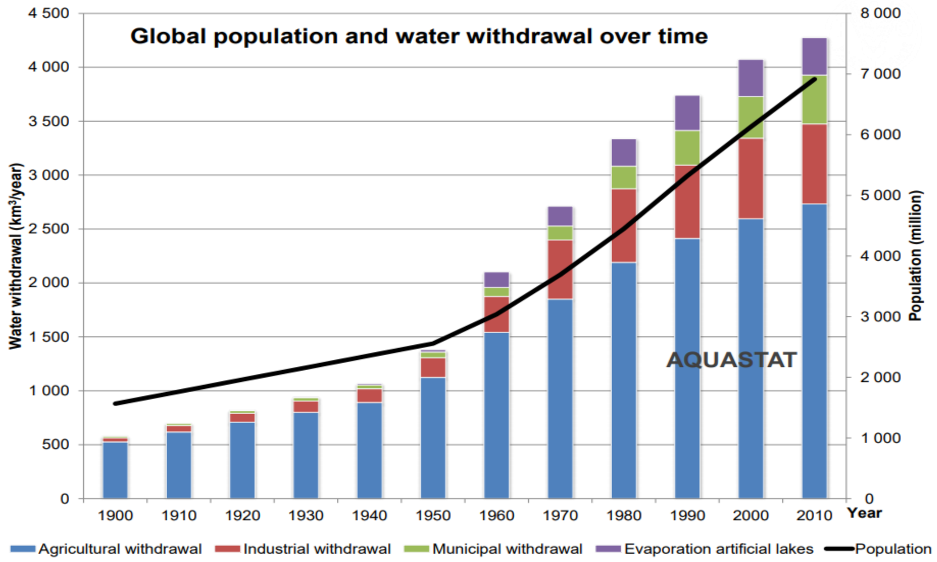


Fig 1.1. Global water withdrawal for the different sectors and population growth (FAO 2016).

Because of increasing demand during the last few decades (water use growth rate is more than twice higher than the population increase rate in the last century (figure 1.1)); freshwater scarcity is one of the critical dilemmas for sustainable development and human society and life. In the World Economic Forum annual risk report (World Economic Forum, 2015, 2019), Water crises are always ranked as one of the highest global risks that humans face. In 2015, 71% or 5.2 billion of global population used a safe drinking water that adequately managed, 6.5 billion or 89% of people employed at least improved drinking water that needs 30 minutes round trip for collecting them (a basic service), but 844 million people couldn't access to even a basic service (WHO, 2018). Clean Water and Sanitation and climate action are set as SDGs goals in 2015.

What is the definition of water scarcity? In the description of UNDP, when available water cannot meet the demand of all sectors (agriculture, industry, domestic, environment, etc.), water scarcity occurs (UNDESA, 2014; UNDP, 2006). There are two types of water scarcity; one is physical, and another one is economical. In the physical shortage, there is not enough water for all our demands, but in the economic deficit, however, there is enough water; because of lack of infrastructure, people can't take enough water for their needs (UNDP, 2006). Easily accessible freshwater is enough of all human beings. Still, because of uneven distribution in some regions, there are water scarcity problems (Oki and Kanae, 2006); for example, the Mediterranean region is home to a 7.3% population but only includes 3% of global water resources (Margat & Treyer, 2004). All of this information shows us that water scarcity is one of the main problems of the World in the 21st century that many societies face.

1.2 NEW APPROACH OVER WATER RESOURCES

Water plays an essential role in our economic and social activities. Demographic and climatic changes will increase the pressure on water resources in the future. Therefore it is necessary for managers, whether in the government or private sectors, to make the right decisions on water allocation (it becomes difficult more and more with increasing demands and pressure on water resources in recent years). The integrated methodology needs to apply instead of the traditional approach to combat with these crises (UN-Water & GWP, 2007; UN-Water, 2008, 2013).

Spatially available water varies region by region; also, it has temporal variation from season to season and interannually. Predicting this variation is very difficult, and one the most challenging part of water managers and planners. In the most developed countries, by building high-cost infrastructure in the supply-side, they overcome this uncertainty to meet sufficient supply and reduce risks. However, it sometimes has negative impacts on the environment and human life. But nowadays, many countries are finding that supply-side solutions alone are not enough to overcome to meet ever-increasing demand; thus, other solutions such as demand management are being addressed to overcome insufficient available water (UN-Water, 2008). Therefore investigating available water and water demand is very important for policymakers.

Water allocates between different sectors and users based on the economic improvement in hydro-economic models (Harou et al., 2009). Considering the economic value of water is essential for water planners and managers for water allocation; also, this type of estimation enables them to find the costs of water scarcity. For this, the first step is to estimate the economic benefit of water use in different sectors (Young, 2005a). After assessing the missing amount of water that can't meet demand, the unrealized economic benefits can be calculated. With understanding water value in various sectors, a policymaker can mitigate the financial costs of water scarcity by managing the available water in the right way.

Fig 1.2. People don't access to clean water (Sobhan 2017).

1.3 PURPOSES, SIGNIFICANCE, AND SCOPE

How much water use has an impact on human economic activity? This study tries to answer this question; therefore, the primary purpose of this framework is how much economic benefit we can gain from using a certain amount of water. Irrigation, Industry, and Domestic (Municipal) is three significant water use sectors (figure 1.3). In the first step, water withdrawal in these three major water use sectors is calculated, and then the economic value of water used for the different sectors is assessed separately. Since there is no holistic study that covers all these three sectors on a global scale, this study tries to assess the economic value of water use at a worldwide level. The best way to project the future is to overview past, but the historical record of different sector water use is quite poor (Flörke et al., 2013). There are only a few studies about water resource assessment and water use at the global level for the 20th century (Flörke et al., 2013; Shiklomanov, 2000; Shiklomanov & Rodda, 2003). Also, the Food and Agriculture Organization (FAO) and the United Nations established global coverage of water-related datasets in different sectors, but still, it is not complete. Sufficient data is essential for understanding water use situations (Showstack, 2011). Therefore, we try to estimate global water withdrawal in a different sector from 1980 to 2010 as past to current conditions (figure 1.3).

This study can be applied for (figure 1.3):

- Building up an allocation policy for making an excellent decision.
- Estimating the costs of water scarcity based on unfulfilled economic benefits (Neverre et al., 2016; Neverre & Dumas, 2015).
- Maximize the economic benefits of the allocated water (Neverre et al., 2016; Neverre & Dumas, 2015).
- Reduce the costs of future water scarcity under global changes in the world (Neverre et al., 2016; Neverre & Dumas, 2015).

1.4 THESIS OUTLINE

Chapter 2 describes the agricultural sector's economic benefit. In this sector, the economic benefit of the agriculture sector is calculated based on the yield comparison approach and amount of irrigation water over grid cells globally.

Chapter 3 explains the industrial sector. In this chapter at the first industrial water withdrawal intensity is calculated in the country scale and distributed to the grid level. The economic value of water in the industrial sector is calculated based on comparison with desalination technology.

Chapter 4 belongs to the domestic sector. In this chapter, domestic water withdrawal is calculated over the grid level with a unique methodology. The economic value of water is calculated with a combination of water demand and willingness to pay on the grid-scale.

Chapter 5 is the synthesis of the economic benefits of water usage for all sectors. This chapter tries to explain which country gains more value for each sector and also in total value. Finally, it shows country base global ranking regarding the economic benefit.

Chapter 6 is the conclusion of the complete study and recommends future work.

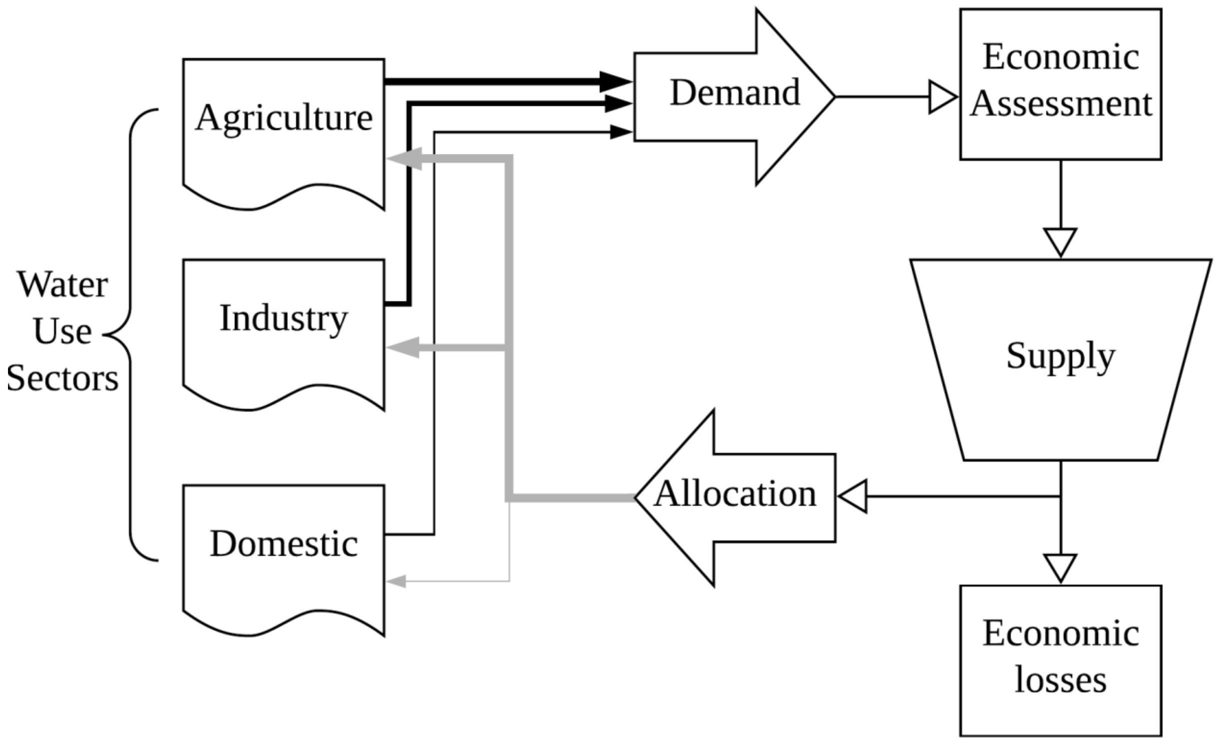


Fig 1.3. Flowchart of idea and objective of this study (width of the arrows show a tentative amount of demands and allocations for different sectors).

Chapter 2: Agriculture

2.1 INTRODUCTION

Water in the agriculture sector is mainly defined as irrigation water (Shiklomanov, 2000). In most of the countries, irrigation water is the highest portion in terms of water use, and it consists of 70% of global water withdrawal (FAO, 2016a; Shiklomanov, 2000). the history of agriculture is almost the same as the history of human life. However, irrigation has been carried out for thousands of years. Still, most of the irrigated land is initiated in the 20^{th} century (Shiklomanov, 2000).

At the end of the 1970s, irrigation expansion was massive in almost all countries, both developed and developing countries. But because of high cost and soil salinization, reduction of water supply source, and environmental problems, this trend was decreased substantially in both developing and developed countries in the 1980s. After that, in some developed countries, irrigated areas dropped or stabilized (Shiklomanov, 2000).

In 2000, 15% of cultivated land was equipped to the irrigation system. Still, in the future, it is expected to increase because with population growth, food demand is also growing, and without high efficient equipment like irrigation systems, it is hard to produce enough food for such a high number of people (Shiklomanov, 2000).

There are several global assortment studies of global irrigation water withdrawal. Some studies used a simple regression model based on national or regional historical trends and socio-economic parameters like GDP and population (Oki et al., 2003; Shiklomanov, 2000).

Döll and Siebert (2000) developed a global digital map of the irrigated area with a spatial resolution of 0.5 degrees for the first time. CROPWAT model (Smith, 1992) calculates potential irrigation water demand for different crops type, and with applying the same methodology, global irrigation water requirements are calculated (Döll & Siebert, 2002). In this way, they calculated five factors (Hanasaki et al., 2013a, 2013b): 1. Potential evaporation of each crop. 2. Effective precipitation. 3. Each crop water requirement. 4. Amount of water consumption of irrigation water demand. 5. Amount of water withdrawal based on irrigation water demand.

Table 2-1 Earlier irrigation water withdrawal studies.

Reference	Irrigation data	Irrigation demand calculation method	Temporal resolution	Spatial Resolution
Döll and Siebert (2002)	Döll and Siebert (2000)	Difference between effective rainfall and potential evaporation.	24h	0.5 degree
Rost et al. (2008)	Siebert et al. (2007)	Difference between plant moisture and potential evaporation.	24h	0.5 degree
Hanasaki et al. (2008a, 2008b)	Döll and Siebert (2000)	Calculated difference between 75% and full saturated as a threshold.	24h	1 degree
Pokhrel et al. (2012)	Siebert et al. (2007)	Used H08 crop calendar and potential evaporation as a root zone moisture deficit.	6h	1 degree
Wada et al. (2014)	MIRCA2000	Difference moisture between saturated soil layer and actual soil layer for paddy and non-paddy field.	24h	1 degree

Table 2.1 summarizes earlier irrigation water withdrawal studies (Nazemi & Wheater, 2015a, 2015b).

Urgent and important are two components that impact on problems ranking through decision-makers, but still water issue problems get low attention from decision-makers despite its importance (Madani, 2019). The bankruptcy of water system is the reality that nowadays many regions of the world face with, but the decision-makers' perceptions from complex of water system dynamics are low; therefore, a coherent and integrated solution is not provided by decision-makers (Madani, 2019; Ristić & Madani, 2019). Economics is one of the ways that can simplify the complexities of the water system in the eyes of water planners and decision-makers.

Irrigation water is the highest share of global water withdrawal and consumption (FAO, 2016a), but irrigation added marginal value is low, mostly in dry regions (Brooks, 2007). Irrigation water has economic value since farmers can produce crops and make profit and revenue through selling their crops (Nikouei & Ward, 2013). The value of water has gotten more attention since the 1992 International Conference on Water and Environment in Dublin (Ziolkowska, 2015b). Based on Hanemann (2006), "water should be recognized as an economic good while it has economic value among all competing water user sectors."

The shadow price of water is one of the ways to express the value of irrigation water (Ziolkowska, 2015b). The concept of the shadow price of water is how much the net production from using a certain amount of irrigation water for different crops. In other words, the shadow price of water is the maximum price of water that farmers can pay; therefore, above that price, farmers don't receive any profits. The shadow price of water can be calculated by the Residual valuation method (Young, 2005a, 2005b). Some studies tried to figure out irrigation water economic value with the Residual valuation method (Berbel et al., 2011; Esmaeili & Vazirzadeh, 2009; Hellegers & Davidson, 2010; Neverre et al., 2016; Ziolkowska, 2015b). But still, an integrated global assessment is neglected. This study tries to estimate the economic value of agriculture water use (irrigation) on a worldwide scale.

2.2 OBJECTIVE

The current study tries to estimate the economic value of the agriculture sector based on the potential irrigation demand from 1980 to 2010 over grid cells.

2.3 METHODOLOGY

Figure 2.1 shows the flowchart of the calculation method of economic benefits related to the agriculture sector.

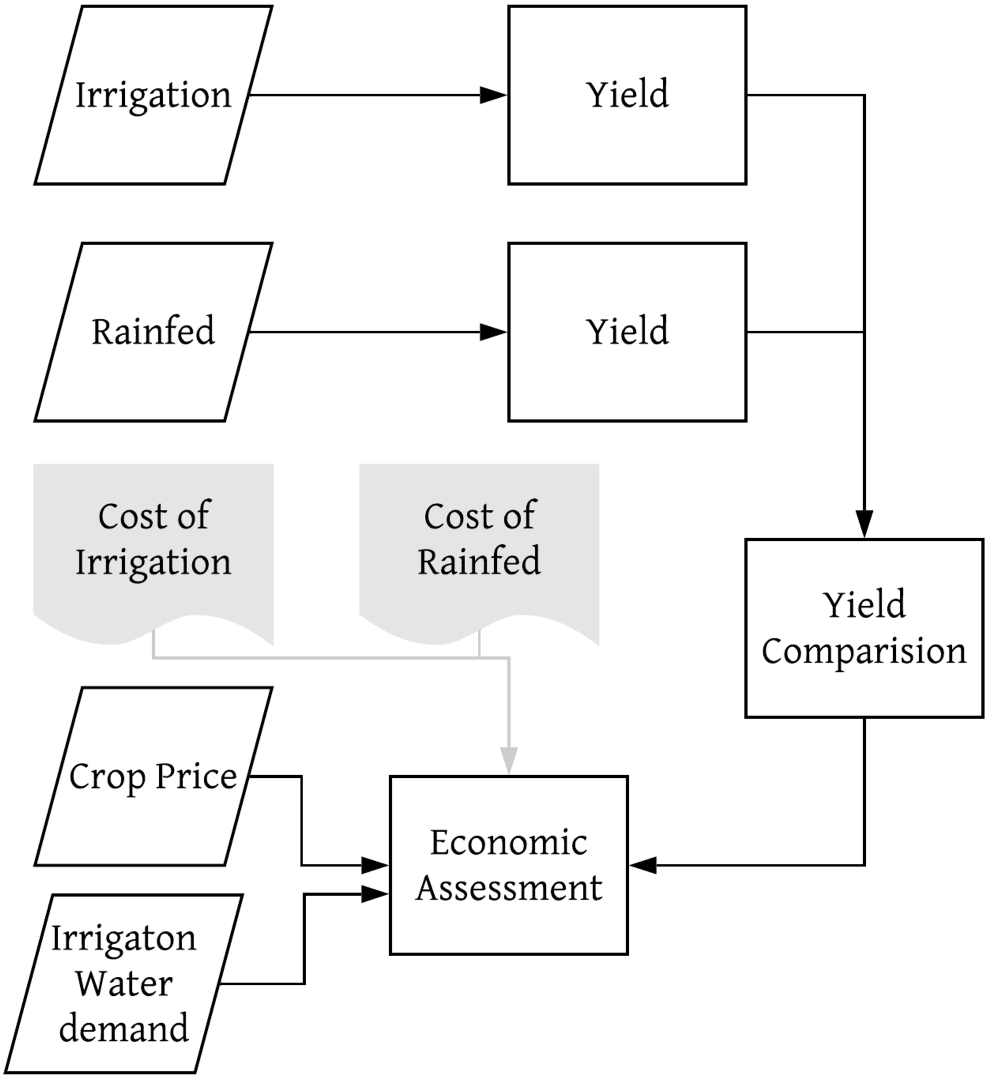


Fig 2.1. Diagram of the agriculture sector water uses the economic benefit calculation process with input data.

2.3.1 Datasets

ISI-MIP

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) provides a framework for comparison of climate impact projections in different sectors and scales (Elliott et al., 2014; Rosenzweig et al., 2014; Schewe et al., 2014; Warszawski et al., 2014). ISI-MIP consists of a lot of global hydrological models, agriculture economic models, GSMs, and forcing data. Since the Oki laboratory is part of this working group, there is an excellent opportunity to access the ISI-MIP server and data.

The dynamic global vegetation and water balance model LPJml (Lund-Potsdam-Jena managed Land) (Bondeau et al., 2007; Rost et al., 2008) is selected for its ability to simulate both irrigation and the rainfed yield on the global scale at the grid level. The yield of irrigation and rainfed is calculated based on "green" and "blue" consumption (green water is precipitation, and it is for rainfed water requirement, Although it can be considered as irrigation water. Bluewater is water withdrawal from the river or water body for irrigation propose).

In the LPJml model, participation, and irrigation water is calculated based on soil moisture, transpiration, soil evaporation, interception, and runoff (Rost et al., 2008). Bellow equations explain how LPJml model calculates agriculture water use:

$$E_p = \min\,(S, D) \qquad 2.1$$

E_p is productive water consumption (mm/d); S and D are supply and demand respectively, which are controlled by the atmosphere. E_p is both for green and blue water.

$$S = E_{max} \times W_{soil,r} \times F_r \qquad 2.2$$

$W_{soil,r}$ is relative soil moisture, and F_r is a fraction of roots.

$$D = \frac{(1 - F_{wet}) \times\ E_{pot} \times \alpha_m]}{1 - \frac{G_m}{G_{pot}}} \qquad 2.3$$

Where F_{wet} is the portion of the day that root is wet; E_{pot} is potential evaporation; αm is 1.391 (maximum Priestley-Taylor conductance); gm is 3.26 mm/s (scaling coefficient) (Rost et al., 2008).

Crop Price

Country scale crop price is accessible from the FAO (Food and Agriculture Organization of the United Nations) database (Bierkens et al., 2019; FAO, 2016b). Since price data is available for 1991-2010, and some countries in some years price are not available, therefore Commodity Markets data from The World Bank (The World Bank, 2019) is used for making simple linear regression models for before 1991 (1980 to 1990). Commodity Markets data is available between 1980 and 2010. Despite FAO data, The World Bank data is the global price. At the first step following (IIASA) 32 macro-regions (Riahi et al., 2017), global countries are grouped to 32 macro-regions. We made a simple regression with the average price of each region and global crop price (The World Bank, 2019). After calculating regional price from 1980 to 2010, each country's rate is calculated based on the linear regression model with the related region from 1980 to 2010. Also, we tried to fill the missing year's price for some countries.

Price data is converted to 2005 USD value:

$$\text{Year 2005 USD value} = \left(\frac{CPI_{2005}}{CPI_t}\right) \times t\ year\ USD\ value \qquad 2.4$$

CPI_t is CPI for each year from 1980 to 2010, and it is collected from The World Bank.

2.3.2 Residual Valuation Method

The residual valuation method is calculated based on the relation between input and output in the crop production function (Ziolkowska, 2015b). The production function is complicated and depends on many other factors, i.e., climatic conditions, irrigation system, topography, fertilizer, topography, management, etc. (Ziolkowska, 2015b). The basic idea of production process value is, the value of the output of production is the accumulated value of all inputs required for production (Hellegers & Davidson, 2010):

$$Y_i \times P_i = X_{1,i} \times P_{1,i} + X_{2,i} \times P_{2,i} + \cdots + X_{n,i} \times P_{n,i} \qquad 2.5$$

Where Y_i is the quantity of production output (here is the amount of crop (ton/ha)) and P_i is output price (here is crop price (USD/ton)). $X_{n,i}$ is required inputs for production Y_i, and "n" is the number of inputs and $P_{n,i}$ is the price of inputs. Water (irrigation water) is one of the input variables:

$$Y_i \times P_i = X_{w,i} \times P_{w,i} + \sum X_{n,i} \times P_{n,i} \quad 2.6$$

$X_{w,i}$ is the quantity of water use (here is irrigation water use (m^3/ton)) for production of Y_i, $P_{w,i}$ is the price of water and $X_{n,i}$ and $P_{n,i}$ is quantity and price of other input variables. Based on residual method concept, it assumes that only water market in the production process isn't competitive (Ziolkowska, 2015b), so when all variables are known except the price of water ($P_{w,i}$), with following equation price of water can be calculated:

$$X_{w,i} \times P_{w,i} = Y_i \times P_i - \sum X_{n,i} \times P_{n,i} \quad 2.7$$

$$P_{w,i} = \frac{Y_i \times P_i - \sum X_{n,i} \times P_{n,i}}{X_{w,i}} \quad 2.8$$

Where $P_{w,i}$ is the shadow price of water for the crop "i" and $X_{w,i}$ is irrigation water use for the production of the crop "i". Based on the residual value method assumption, when all inputs value except $P_{w,i}$ are known, with Eq. (2.8) the unit price of irrigation water (USD/m^3) can be calculated (Ziolkowska, 2015b).

As mentioned, the crop production function is complicated, since it depends on many variables, therefore calculating the price of irrigation water with Eq. (2.8) is almost impossible for the global level. With utilizing yield comparison approach (Neverre et al., 2016; Turner et al., 2004) followed the concept of residual value method, the value of irrigation water can be obtained as follows:

$$P_{ir} = \frac{TNB_{ir} - TNB_{rf}}{W_{ir}} \quad 2.9$$

Where P_{ir} is the value or price of the unit amount of irrigation water (USD/m^3). TNB_{ir} (USD/ha) is an overall net benefit from irrigation cultivation products for the particular crop, and TNB_{rf} (USD/ha) is a total net benefit that would be generated if the same crop was cultivated with rainfed. W_{ir} (m^3/ha) is irrigation water used for the production of the same crop. By giving details, Eq. (2.9) can be rewritten as follows:

$$P_{ir} = \frac{[Y_{ir} \times P_{crop} - Cost_{ir}] - [Y_{rf} \times P_{crop} - Cost_{rf}]}{W_{ir}} \quad 2.10$$

Where Y_{ir} is irrigation yield and $Cost_{ir}$ is irrigation cultivation cost for the specific crop, and also Y_{rf} and $Cost_{rf}$ are the same terms for rainfed. Total economic value through irrigation water use is obtained with Eq. (2.11):

$$V_{tot,ir} = [Y_{ir} \times P_{crop} - Cost_{ir}] - [Y_{rf} \times P_{crop} - Cost_{rf}] \quad 2.11$$

$V_{tot,ir}$ (USD), is the total economic benefit that can be generated by using the irrigation system. Since obtaining all cost of both irrigation and rainfed is difficult; therefore, we assumed that the cost of irrigation and rainfed is identical except for the installation of irrigation equipment (Neverre & Dumas, 2016):

$$Cost_{ir,inst} = Cost_{ir} - Cost_{rf} \quad 2.12$$

$$P_{ir} = \frac{[Y_{ir} \times P_{crop} - Cost_{ir,inst}] - [Y_{rf} \times P_{crop}]}{W_{ir}} \quad 2.13$$

$Cost_{ir,inst}$ is the cost of irrigation installation (USD/ha). This study uses Eq. (2.13) for calculation of the shadow price of irrigation water as the economic value of water use in the agriculture sector.

2.3.3 Cost of irrigation installation

For calculating $Cost_{ir,inst}$, 248 irrigation installation projects' data is collected from FAO (FAO 2016). These data are consisting of irrigation site area, cost, and name (country and site name). As shown in figure 2.2, the total irrigation size and the total cost are correlated. The regression was performed by taking the natural logarithm, and the goodness-of-fit (R^2) of 0.74 indicates that it has significant explanatory power.

In this study, we differentiate the unit cost of irrigation installation for each country by applying country GDP per capita (although it depends on other factors, e.g., land type and irrigation system). Finally, the total irrigation installation cost is calculated by taking multiple linear regression between irrigation cost, irrigation size, and country GDP per capita. In this way, 70% of available data is used for training, and 30% of data is used for the training model. Table 2.2 summarized the statistical details of the dataset.

Table 2.3 shows multiple linear regression results (coefficients) using 70% of the data as training. The intercept is 7.6.

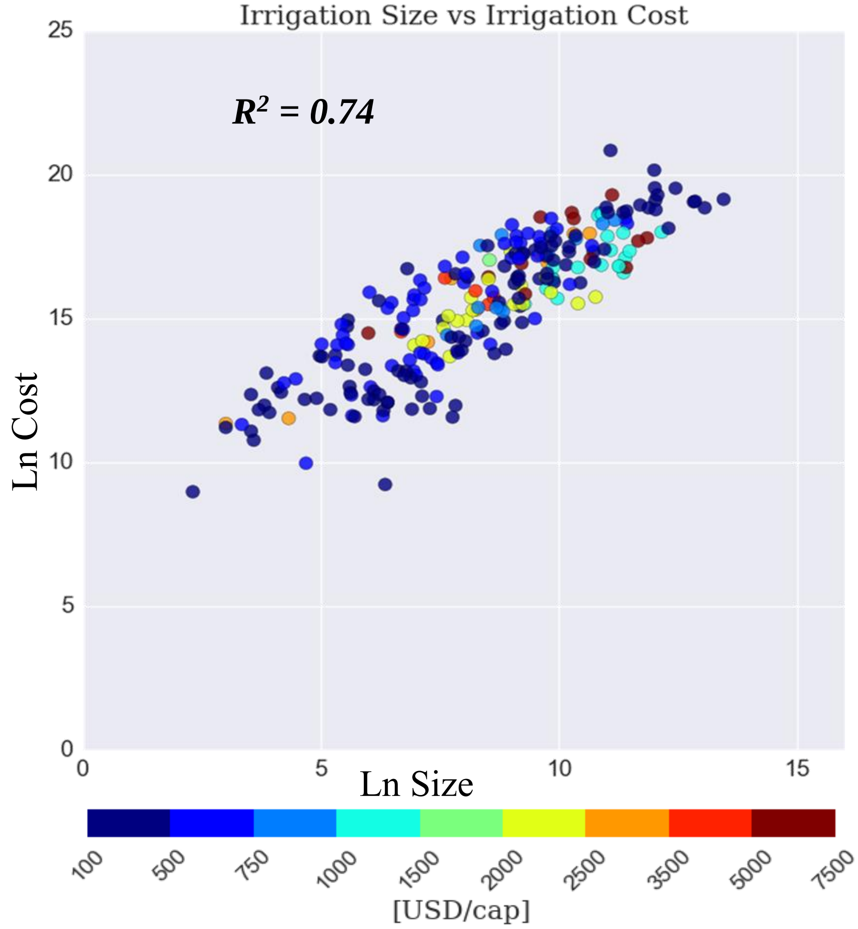


Fig 2.2. Correlation between the total size and cost of irrigation installation (Colour is country GDP per cap of each project).

Table 2-2 Statistical details of the dataset are used in multilinear regression (after taking a natural logarithm).

	Size	Cost	GDPC
count	248.000000	248.000000	248.000000
mean	8.359199	15.547684	6.549035
std	2.291266	2.322390	0.901555
min	2.302585	8.982433	4.931249
25%	6.803155	13.803357	5.876019
50%	8.575284	15.787026	6.484425
75%	9.883398	17.340651	6.951633
max	13.460263	20.846009	8.820416

Table 2-3 Multilinear regression coefficients. They are used for calculating irrigation installation costs.

	Size	GDPC
Coefficient	0.87	0.104

Results show that for a 10 unit increase in "Size", there is an increase of 7.4 ($10^{0.87}$) units in the cost of the irrigation. Similarly, ten units increase in "GDPC" results in an increase of 1.27 ($10^{0.104}$) units in the cost of the irrigation.

Based on multiple linear regression results, cost of irrigation can be calculated by the following equation:

$$Cost_{ir,inst} = e^{7.6} Size^{0.87} GDPC^{0.104} \tag{2.14}$$

Where $Cost_{ir,inst}$ is irrigation installation cost (2005USD), and Size is irrigation area (ha), and GDPC is country GDP per capita (2005USD).

For model validation, 30% of data is used to project irrigation costs. Figure 2.3 shows the difference between the actual value and the predicted value.

Since $Cost_{ir,inst}$ is the total irrigation installation cost; therefore, we need to divide by irrigation equipped area to get irrigation installation cost per hectare.

While R^2 of multiple linear regression is 0.74, R^2 of actual and projected value is 0.73. Therefore, it indicates that the model has significant explanatory power.

For model evaluation, three evaluation metrics are used:

1. **Mean Absolute Error** (MAE) is the mean of the absolute value of the errors. It is calculated as:

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n} \tag{2.15}$$

2. **Mean Squared Error** (MSE) is the mean of the squared errors and is calculated as:

$$MSE = \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n} \tag{2.16}$$

3. **Root Mean Squared Error** (RMSE) is the square root of the mean of the squared errors:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \overline{y_i})^2}{n}} \quad 2.17$$

With finding the values for these metrics using our test data, **MAE=0.98**, **MSE=1.2,** and **RMSE=1.1.** The amount of Root-mean-square error is 1.1, which is less than 10% of the cost mean value, which is 15.55. As a result, our algorithm was accurate and can make reasonably good predictions.

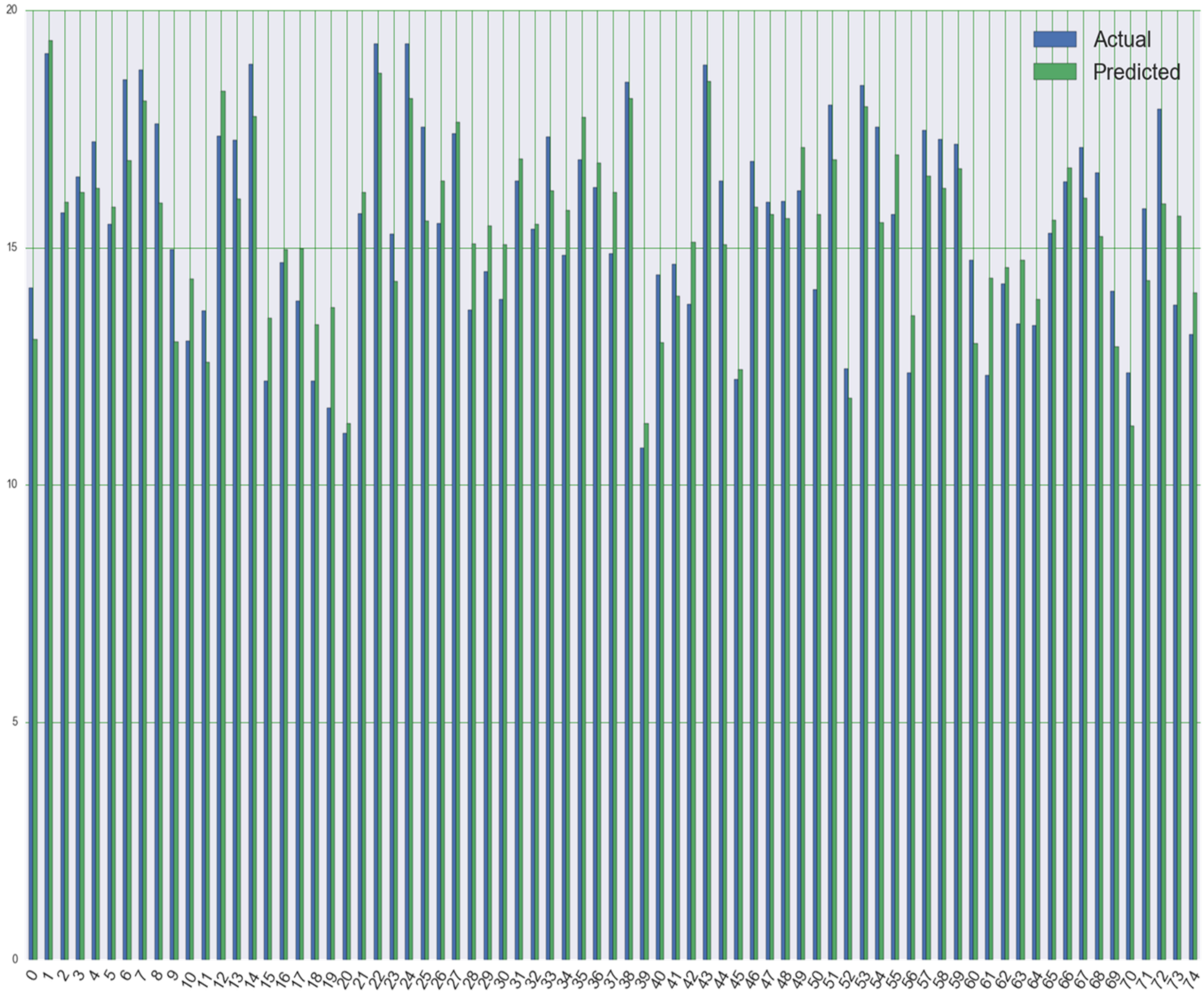


Fig 2.3. Difference between the actual value and predicted irrigation cost value

2.3.4 Calculating the cost of irrigation on the global scale

Now we need to apply the irrigation cost model on a worldwide scale. For this, the Global Map of Irrigation Areas (GMIA) from FAO (Siebert et al., 2013) is used. This map shows the amount of area equipped for irrigation system around the year 2005 in hectare with a resolution of 5 minutes. By replacing area equipped for irrigation (AEI) data with Size in Eq.2.15:

$$Cost_{ir,inst} = e^{7.6} AEI^{0.87} GDPC^{0.104} \qquad 2.18$$

By applying Eq.2.18 to each grid cells, irrigation cost can be calculated on the global scale over the grid level. Figure 2-4 shows the irrigation cost result for the year 2005 with a resolution of 5 minutes.

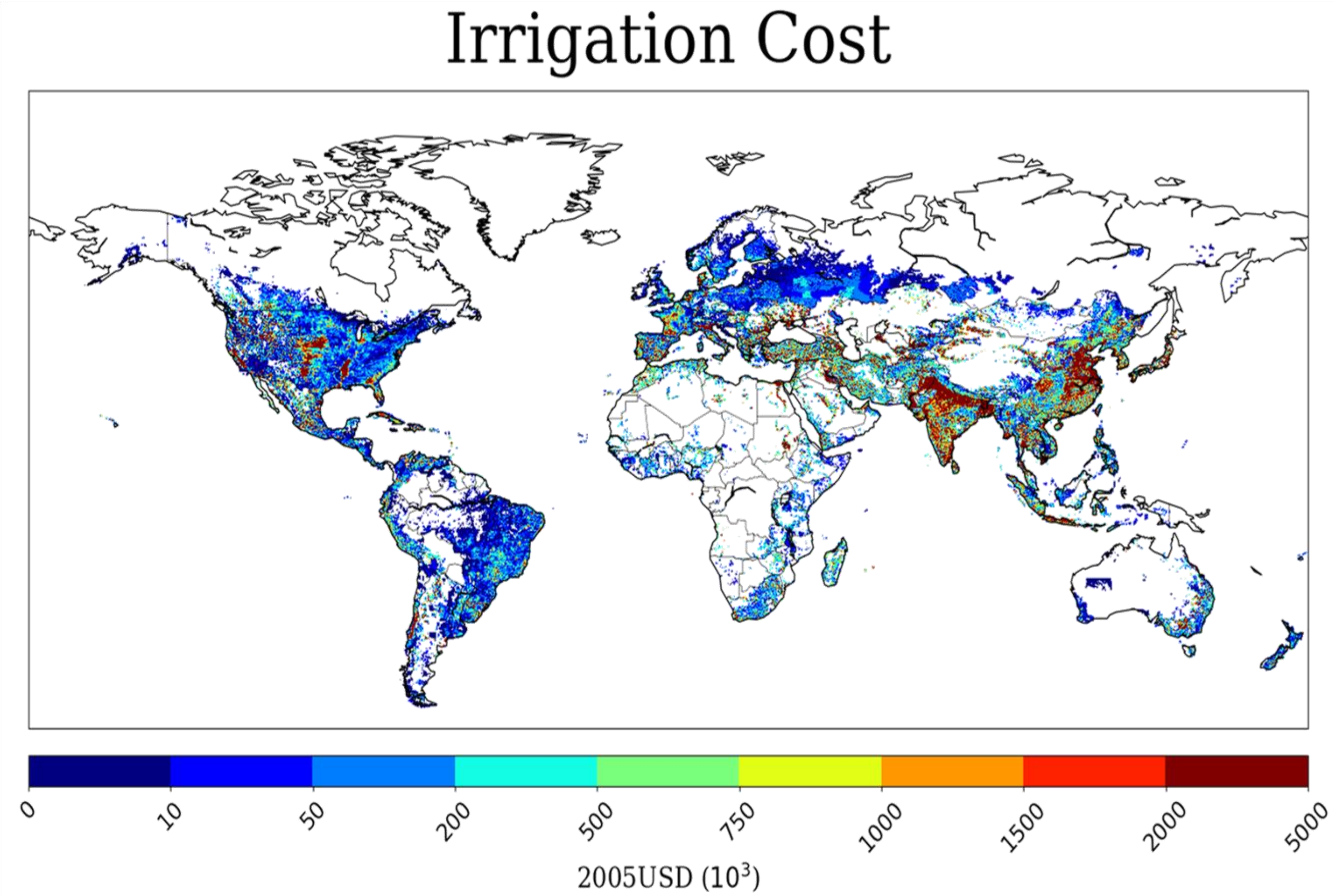


Fig 2.4. Irrigation cost for the year 2005 with a resolution of 5 minutes (0.083 °× 0.083°)

Since the resolution of our other data are 30 minutes, therefore we upscaled irrigation cost result in 30 minutes (0.5°× 0.5°) (Figure 2-5).

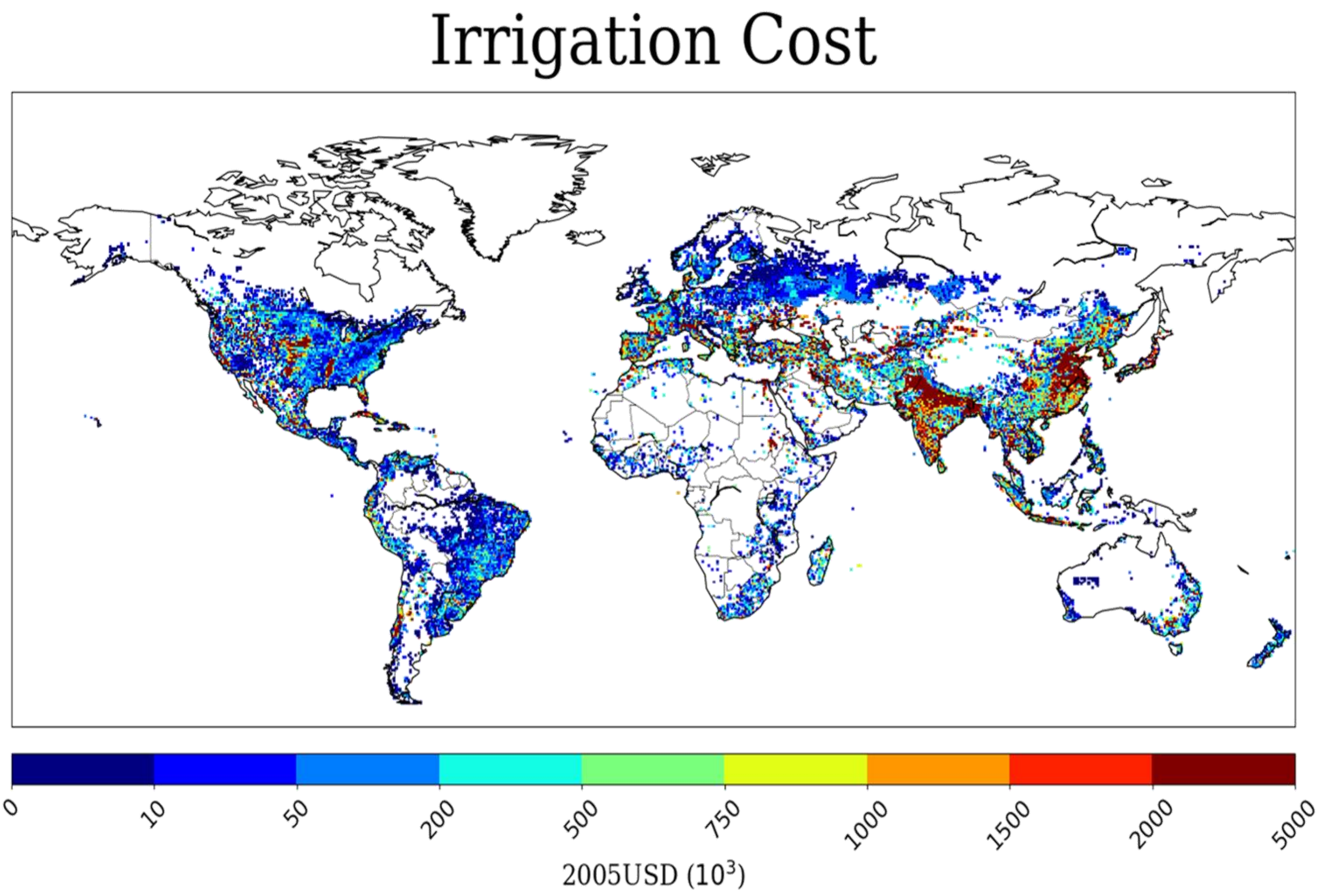


Fig 2.5. Irrigation cost for the year 2005 with a resolution of 30 minutes (0.5˚× 0.5˚)

Area equipped for irrigation (AEI) data is only available for year around 2005, therefore following Hanasaki et al. (2013), area expansion is considered 0.3%yr $^{-1}$. AEI for 1980 to 2010 is calculated as:

$$\textbf{Before 2005}: AEI = (1 - 0.003)^{2005-t} \qquad 2.19$$

$$\textbf{Before 2005}: AEI = (1 + 0.003)^{t-2005} \qquad 2.20$$

AEI is an area equipped for irrigation (ha), and ‘t‘ is the year in which the cost is calculated. By dividing $Cost_{ir,inst}$ with A_t which is irrigation harvested area (ha) for all crops (obtained from MIRCA2000 for around the year 2000 and same as AEI, 0.3%yr^{-1} is considered as an area expansion), irrigation installation cost per hectare can be calculated. For converting unit to USD/m^3, need to multiply W_{ir} by 10.

2.4 RESULT

2.4.1 Crop Yield

Figure 2.6-9 shows crop yields for four crops (Maize, Rice, Soya, and Wheat) globally for both irrigation and rainfed from 1980 to 2010.

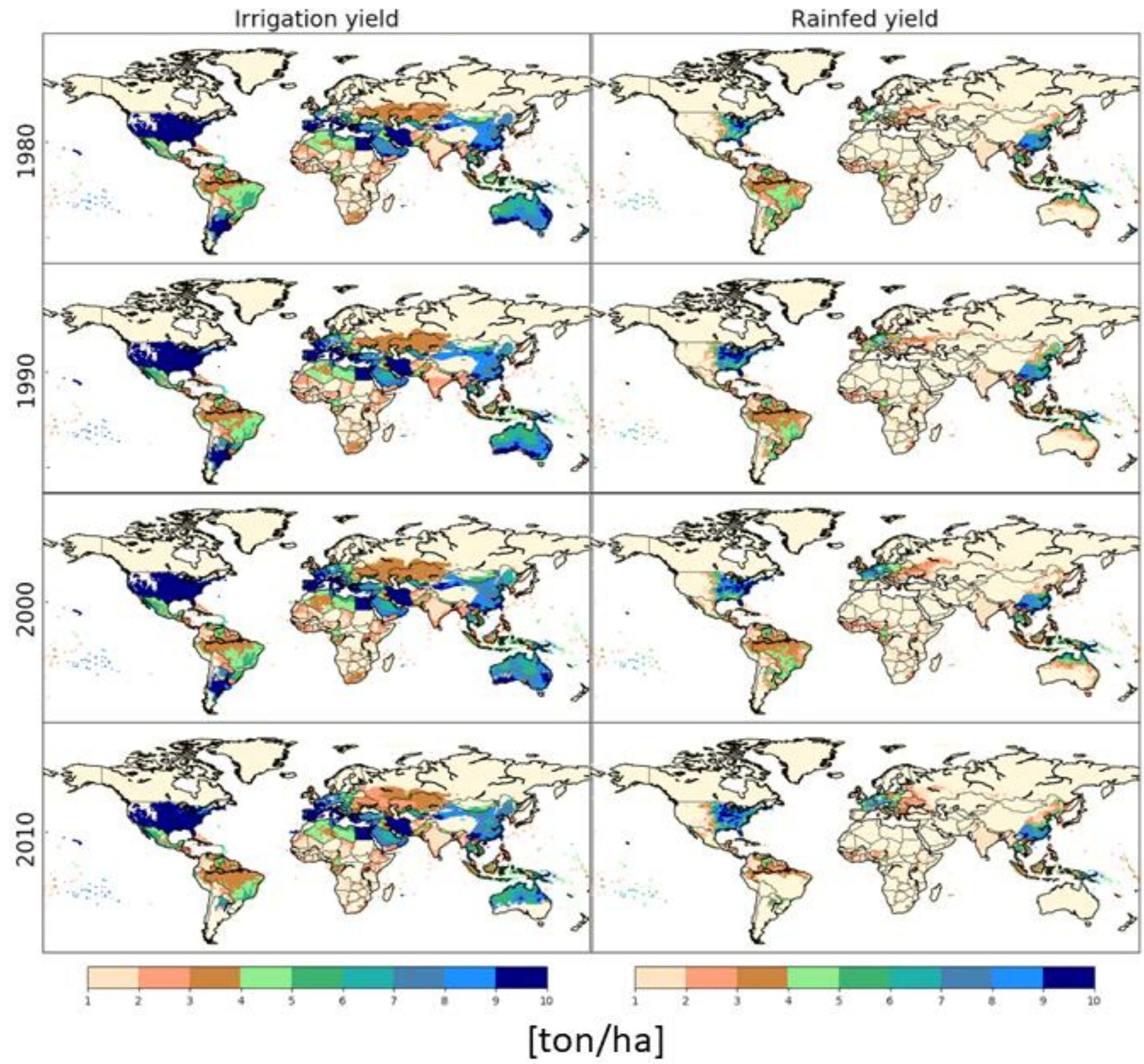


Fig 2.6. Maize potential yield for irrigation and rainfed over the grid level (0.5˚×0.5˚).

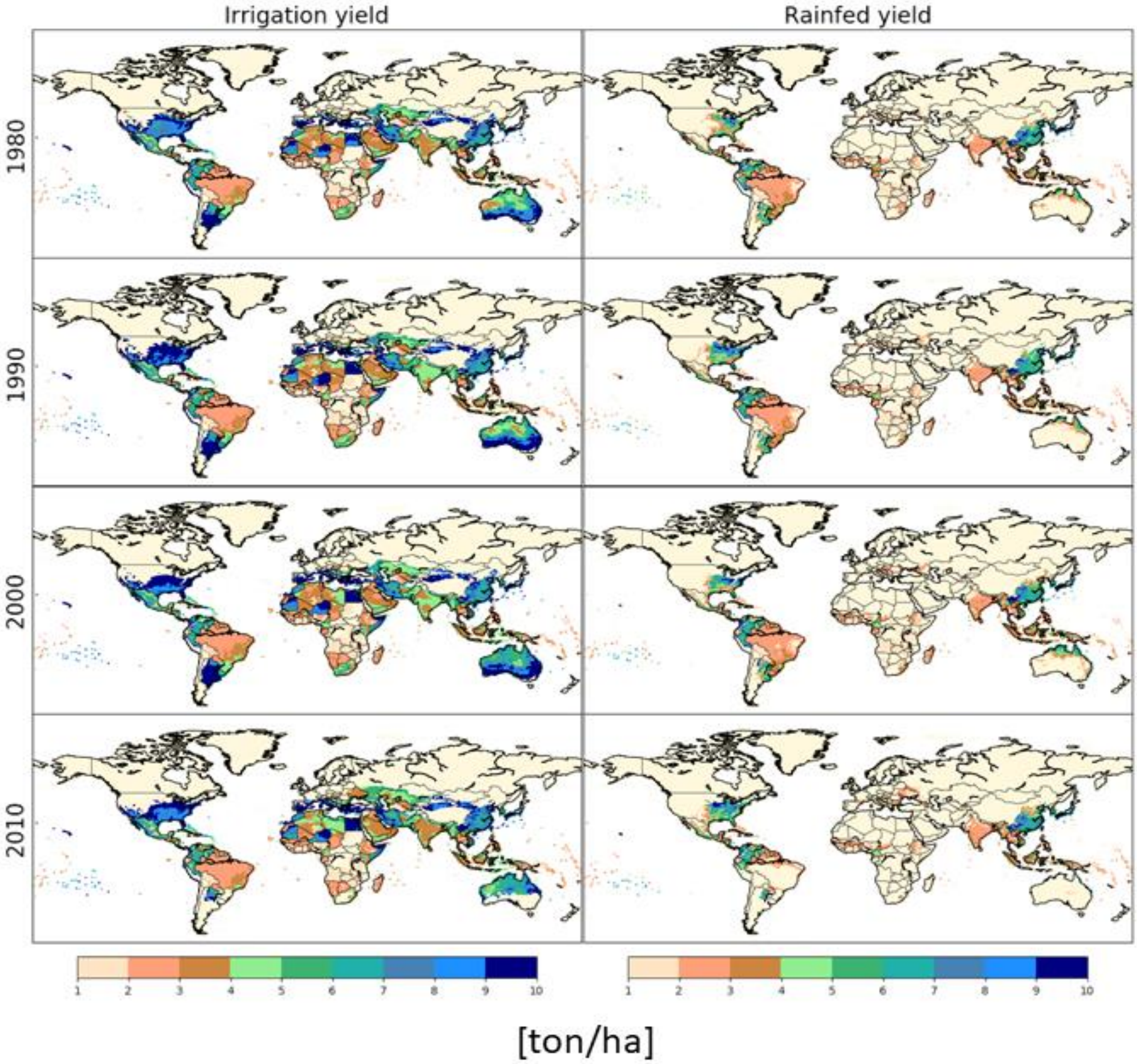


Fig 2.7. Rice potential yield for irrigation and rainfed over the grid level (0.5˚×0.5˚).

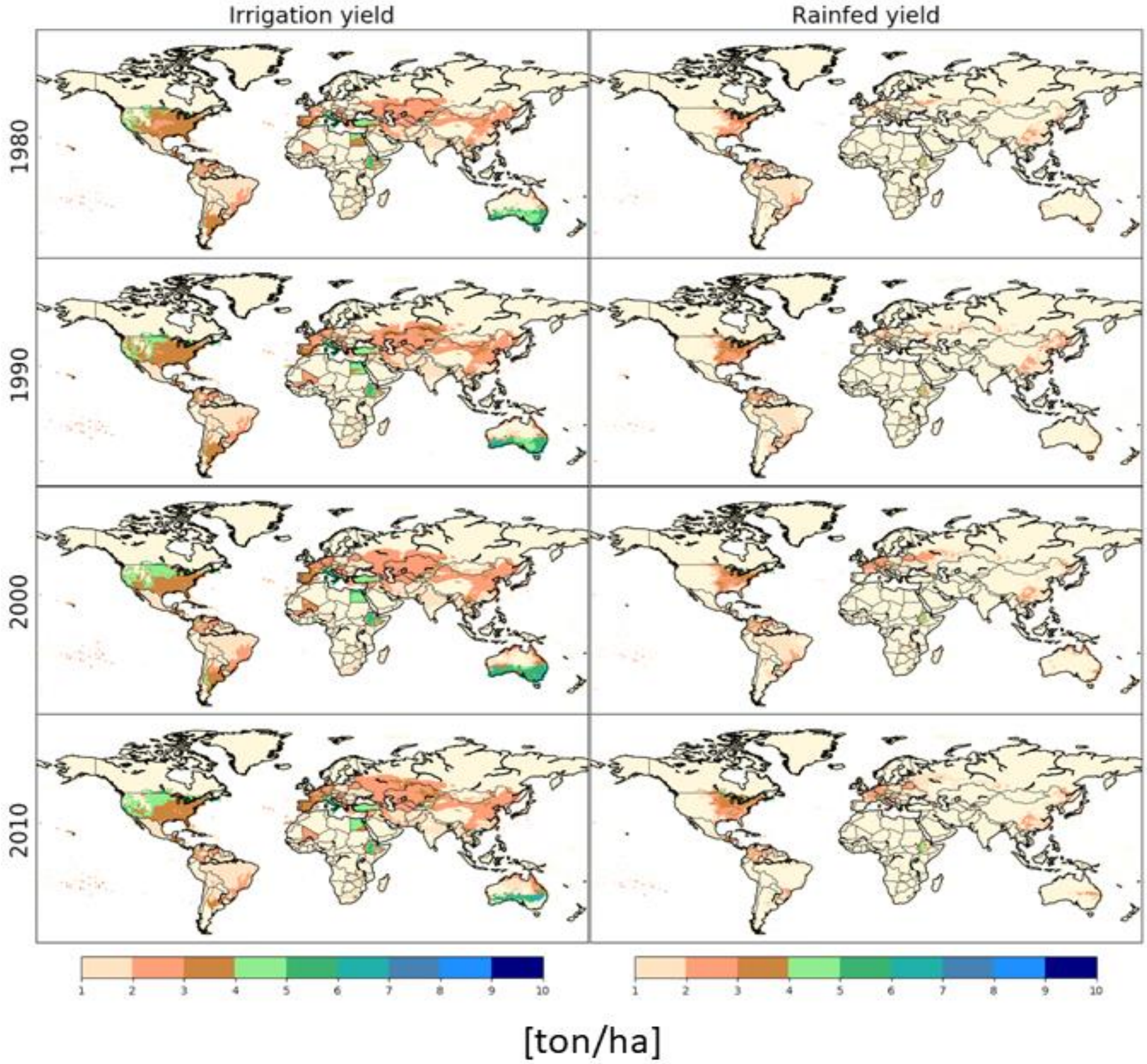


Fig 2.8. Soy potential yield for irrigation and rainfed over the grid level (0.5˚×0.5˚).

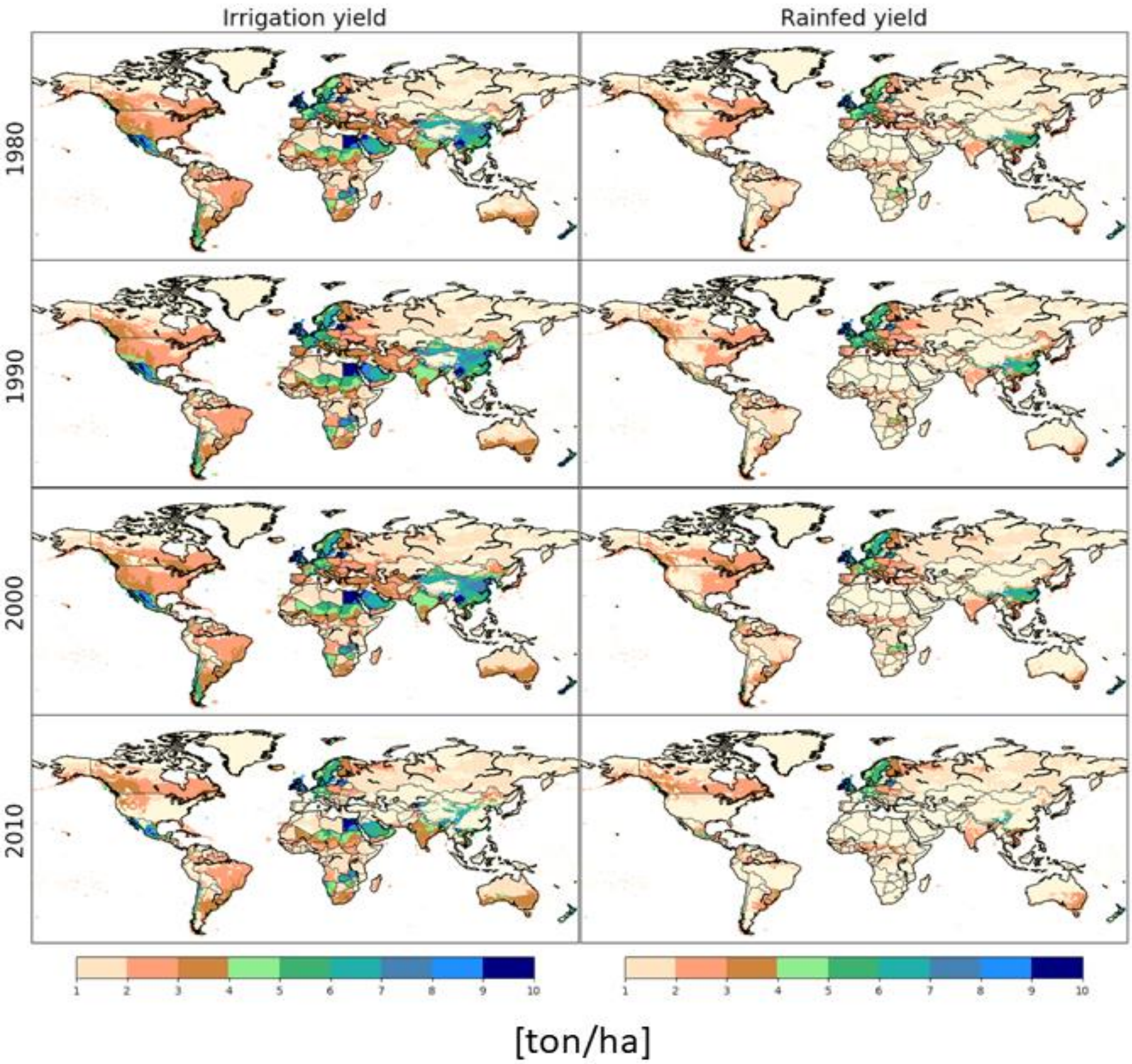


Fig 2.9. Wheat potential yield for irrigation and rainfed over the grid level (0.5˚×0.5˚).

Irrigation yield is potential, and it is not an actual yield. Maize shows more potential yield in irrigation, and soy shows the least. Soy yield is mostly less than 5 ton/ha in irrigation and meager amount in rainfed. Although maize cultivation with irrigation shows substantial yield, with rainfed also shoes high amount mostly in the United States, China, and some parts in Europe, it is also the same for rice. Since rice shows high yield for rainfed in the United States, China, and Japan. In terms of wheat cultivation, the yield is less than rice in the irrigation system, and also yield in rainfed is relatively low.

Yield loss in 2010 is remarkable, mostly in Australia and Middle Eastern countries both in irrigation and rainfed.

Figure 2.10 and 2.11 shows global annual yield average for irrigation and rainfed, respectively.

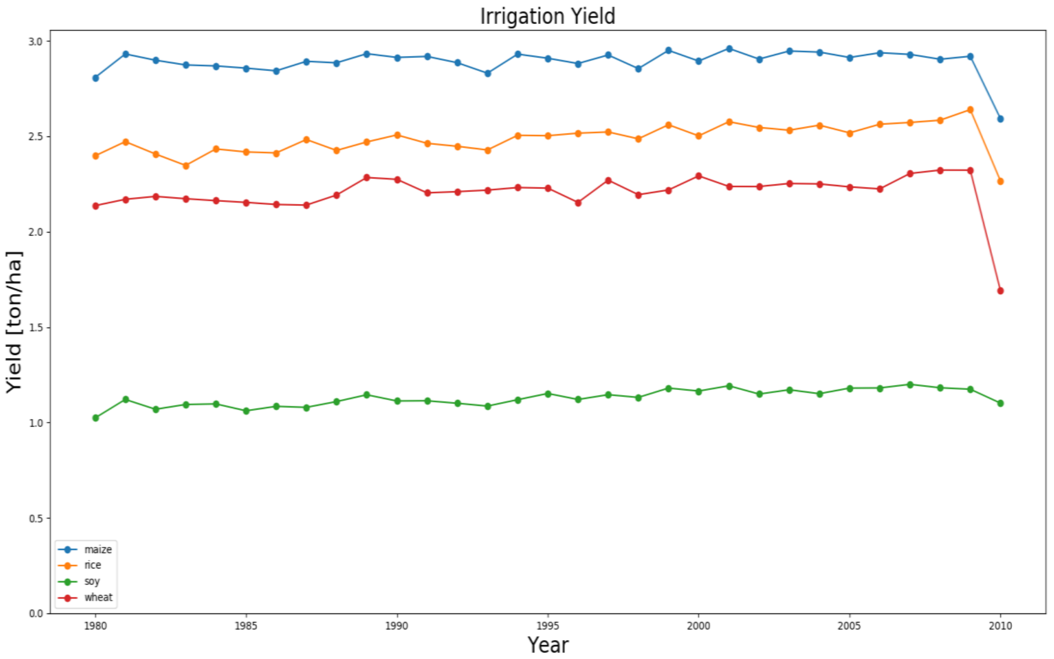


Fig 2.10. Global yearly average irrigation yield.

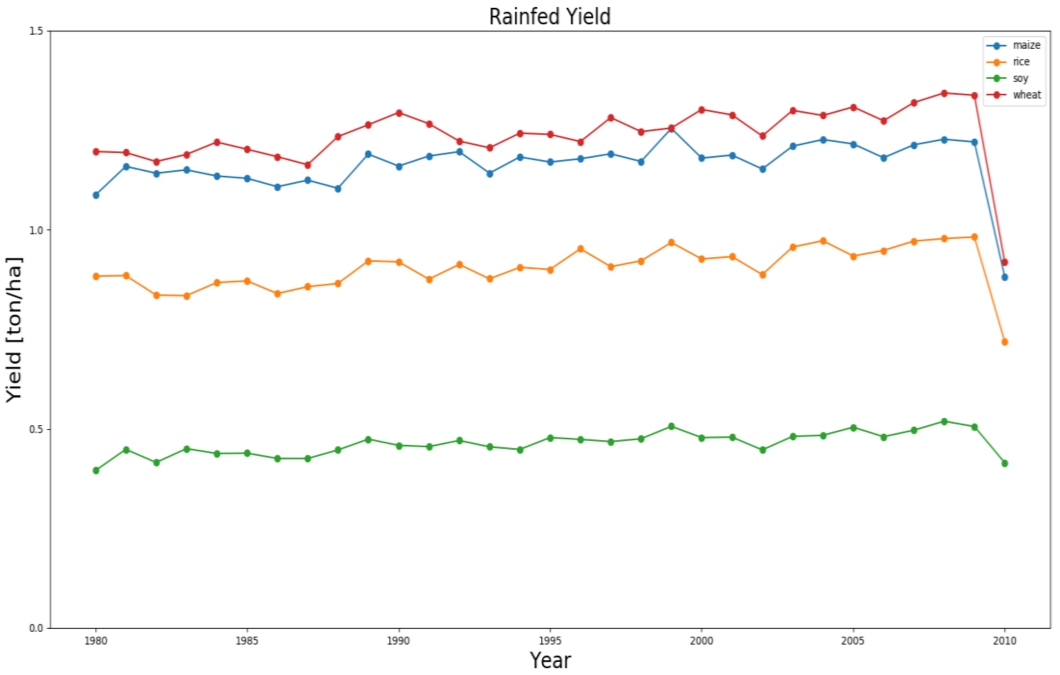


Fig 2.11. Global yearly average rainfed yield.

Maize has the highest yield in irrigation, and wheat has the highest yield in rainfed. The yield amount of maize in irrigation is almost two times higher than the least yield crop (soy), and also in rainfed, it has more than two times the gap between wheat and soy yield. Soya yield is around one ton/ha and 0.4 ton/ha for irrigation and rainfed, respectively, and it remains almost at the same level over time.

Yield remains at the same level during the time in irrigation for almost all crops with low fluctuation, but the rainfed have higher variation in comparison with irrigation.

Yield decline was significant for all crops in 2010, and the reduction amount is higher in rainfed. Wheat has the highest reduction; also, soy has the least. Investigating crop reduction reason is out of the scope of this study. Still, while the highest loss is captured in rainfed, it can be related to climate variables since rainfed yield is highly depended on climate variables and somehow controlled by them. It is a high possibility that strong El Niño occurred in 2010.

By comparing the yield of irrigation and rainfed, potential added yield by irrigation can be obtained. Figure 2.12 shows the yield gap between irrigation and rainfed (ton/ha). As is expected, maize has the highest value (more than 1.5 ton/ha). For maize and soy potential added yield is increased in 2010, while for wheat and rice are the inverse. Same as yield in irrigation all crop shows small variation during the time.

It should be noted that the global average potential added yield value is all positive and higher than zero during the time. It shows in global irrigation yield is always higher than rainfed, and it is an opportunity that adds value by irrigation. Although on a smaller scale (country or grid), rainfed cultivations can be had a priority. This case might happen in high precipitation regions such as Europe or eastern Asia for cultivation crops like rice.

In general, potential added yield can be divided into four categories. First is high value, it means maize, second is relatively high value; rice and the third is relatively low value; wheat and the last is low value; soy. Of course, without considering other factors such as price and amount of irrigation, still, it is not possible to conclude which crop has the highest economic potential in terms of irrigation.

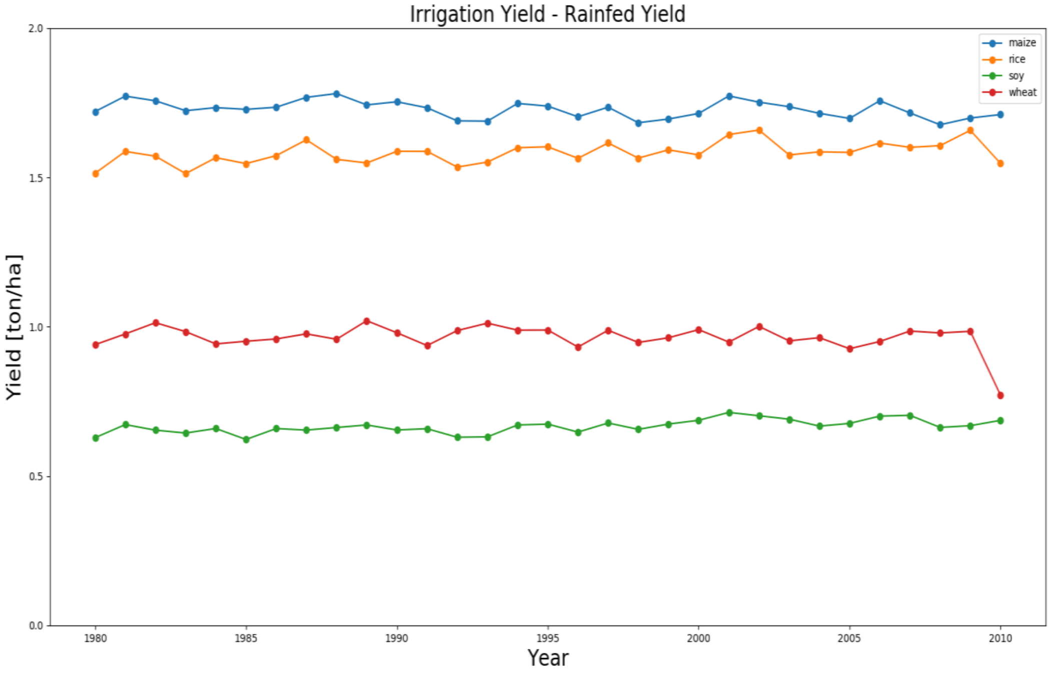


Fig 2.12. The global annual average of potential added yield by irrigation (ton/ha) (yield difference between irrigation and rainfed).

2.4.2 Shadow Price of Water

In the previous section, the yield gap between irrigation and rainfed is calculated. By using yield gap information, the shadow price of water in the agriculture sector is calculated based on section (2.3.1) method as the economic value of water. Figure 2.13 shows crop price change during the time from 1980 to 2010 in the 2005 USD value. After two global crises that caused commodity price increases (in the 1950s because of the Korean War, and 1970s because of oil crises), also after 2004 and 2005; commodity price is increased again (Baffes & Dennis, 2013). Although after 2008, it tends to decrease, the rate is still higher than before 2004. Understanding the reason for price increases for post-2004, 2005 is not directly related to this study, but investigating water value in economic perspective may help policymakers toward the more accurate result.

For all crops, the maximum price was captured in 1980 and 1981. In 1980 soy had the highest rate (almost 712 2005USD/ton), and wheat had the lowest price (nearly 435 2005USD/ton); it is almost a 64% difference. After 1980, the price has a significant decrease in all crops. Maize has the highest potential yield, and soy has the lowest; therefore, it has probably impact on price, but for rice with high yield, price is still high. For wheat, since it has the highest global average rainfed yield, it can link to low cost and finally low price.

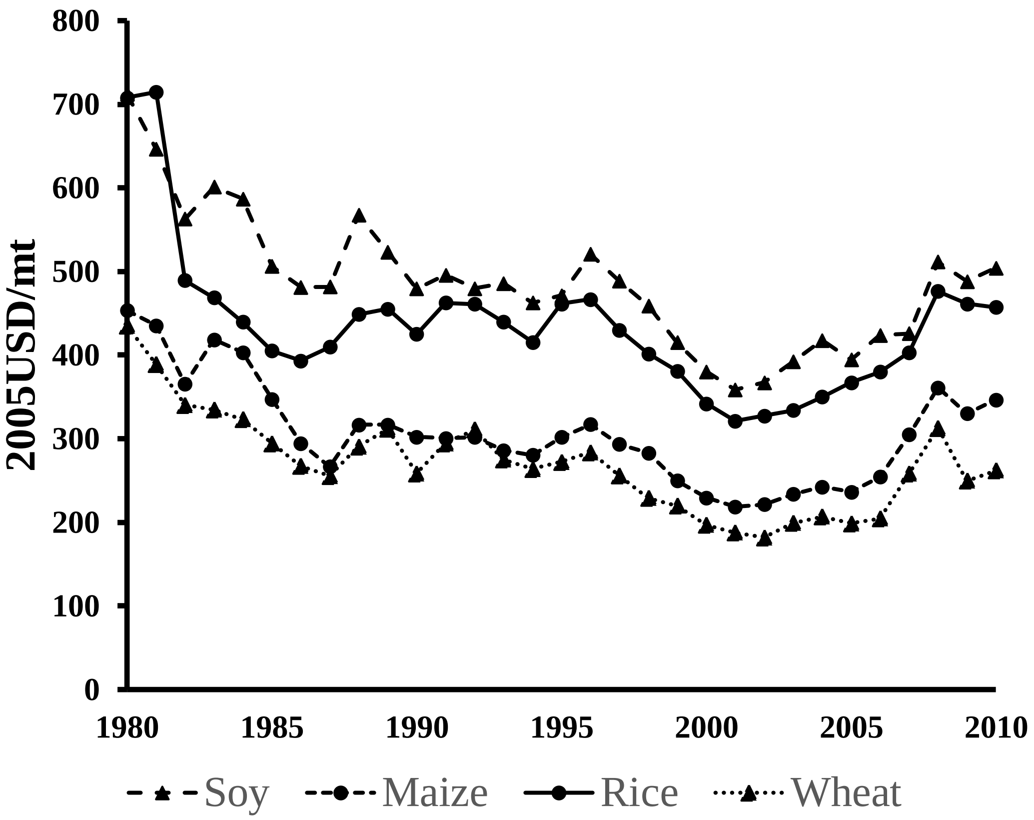


Fig 2.13. Price changing during the time for different crops in 2005 USD value (country reconstructed price data (section 2.3.1) and The FAOSTAT (FAO, 2016b) is converted to global average price).

Figure 2.14-17 shows the global distribution of the economic value of water at grid-scale from 1980 to 2010 for maize, rice soy, and wheat, respectively.

In maize cultivation, the shadow price of water (figure 2.14) is almost less than 0.5 USD/m³ in all of the world, although, in some places, it had more than 0.5 USD/m³ value in 1980. The economic value of maize irrigation water shows as same as the price trend, it means from 1980 to 2000 it is decreasing, and from 2000 to 2010, it is increasing. Still, despite the price, economic value is higher in some regions, especially in South America, in 2010 compared to 1980. Shadow price in 1990 and 2000 is almost at the same level. In general, maize cultivation shows more economic value in the arid region, such as the Middle East, Australia, and The United States.

The economic value of rice irrigation water (figure 2.15) is higher than 0.3 USD/m³ in a lot of places, and even in some countries, it is higher than 0.5 USD/m³, such as the United States, China, Spain, Iran, and Australia. Rice irrigation water's shadow price also follows the same trend as maize, and it is decreasing to 2000 and increasing toward 2010. Although in 2010, shadow price increases in comparison with

1980 in some regions like South America, the considerable reduction occurs in Australia. In The United States, in some part, shadow price is decreased, and, in some others, it increases. Shadow price in major rice-producing countries, e.g., India and Southeast Asia counties, it doesn't exceed 0.2 USD/m³, it can be related to relatively high rainfed yield and low irrigation yield compared to other regions.

Soy has the least yield in both irrigation and rainfed, but with a high price. In 1980 the shadow price of soy irrigation water (figure 2.16) was less than 0.3 USD/m³ in almost all of the world (except for the United States and some West European regions), and the global trend tends to decrease from 1980 to 2010 to below 0.2 USD/m³. It seems the shadow price had the lowest value in 2000. In 2010, in some parts of Brazil, shadow price exceeded the 1980's amount. In the United States, Central Asia, and China, shadow price is decreased a lot comped to the 1980's vale in 2010.

Wheat has the most coverage in the world. The economic value of wheat irrigation water is higher than 0.3 USD/m³ in some parts of South America, Africa, China, and the Middle East (for others is below 0.2 USD/m³) in 1980 (figure 2.17). Same as other crops, wheat shadow price is also decreased from 1980 to 2000, although still in some parts of South America and Africa, shadow price is higher than 0.2 USD/m³ in 1990 and 2000. It seems the shadow price reaches the bottom level in 2000 and increase to 2010. In 2010, it had the least cultivation area in comparison with other years. Since wheat has the highest global average yield in rainfed, due to significant El Niño event in 2010, crop production decreased, and at the same time, shadow price grew up compared to 1990, 2000, and even 1980 in some regions.

In general, for all crops except in maize and rice 1980, the shadow price of irrigation water is mostly below 0.2 USD/m³ (even bellow 0.1 USD/m^3 in some regions). Rice has the highest shadow price, and it was maximum in 1980. In all crops, the global trend of shadow price decreases once from 1980 to 2000, and it increases again to 2010.

Blue color areas in all maps show the places in which the shadow price is minimal and close to zero and even negative (dark blue). Negative shadow price means increasing crop yield through irrigation can't compensate irrigation installation cost, and rainfed cultivation has priority in those areas. Mazie and wheat had more negative values. Mostly in wet regions like Europe, the shadow price is negative.

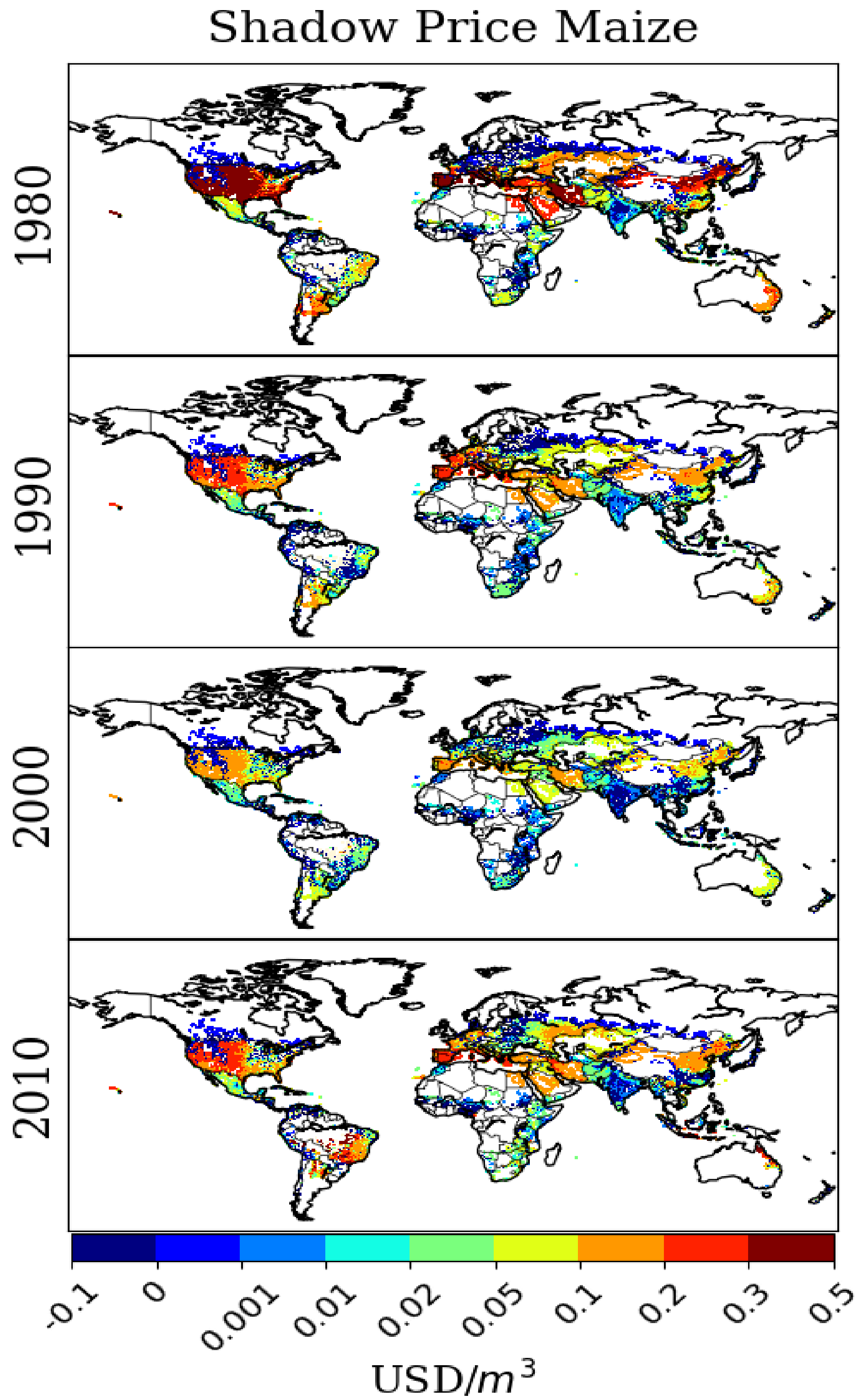


Fig 2.14. Shadow price as the economic value of irrigation water for maize.

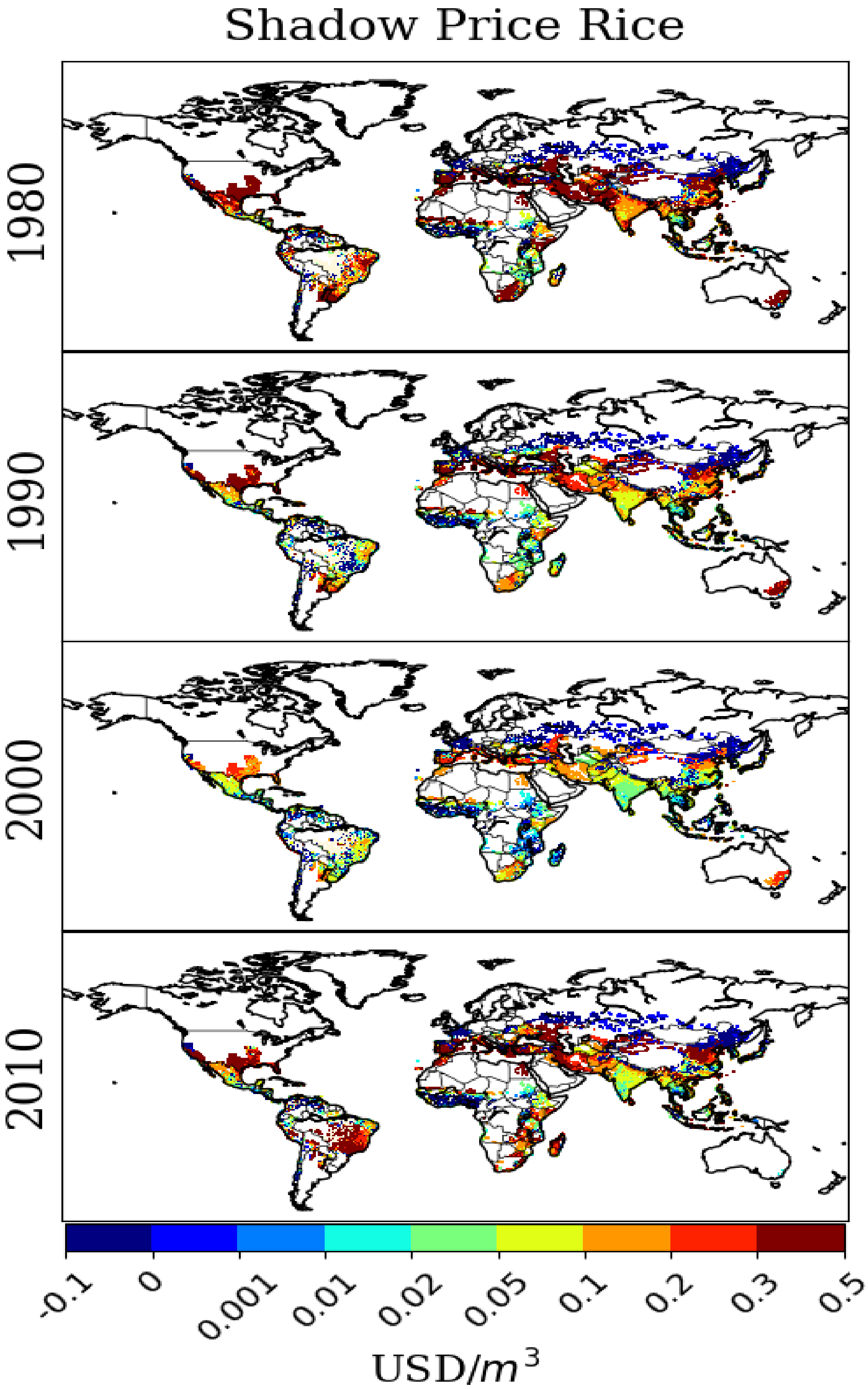


Fig 2.15. Shadow price as the economic value of irrigation water for rice.

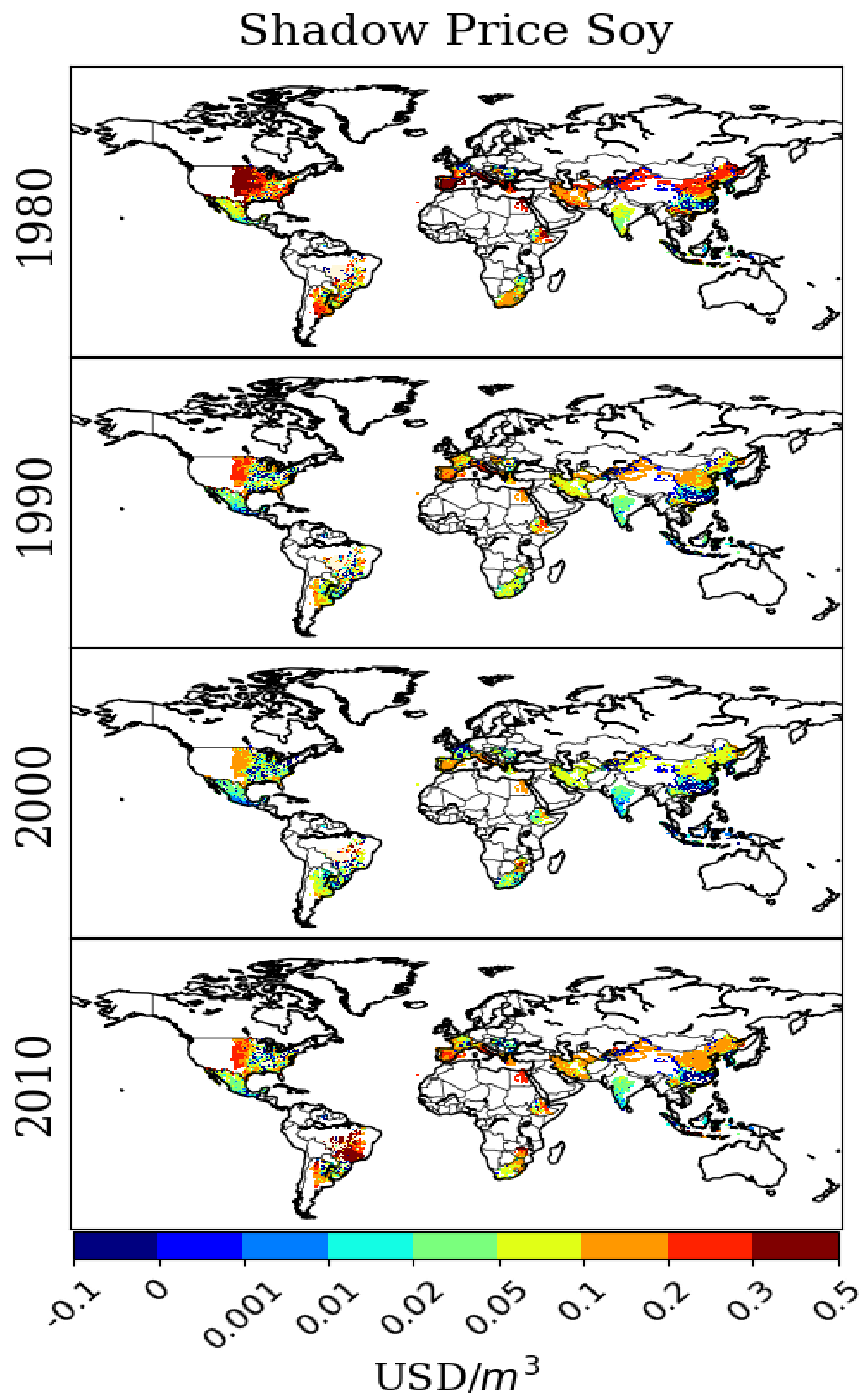


Fig 2.16. Shadow price as the economic value of irrigation water for soy.

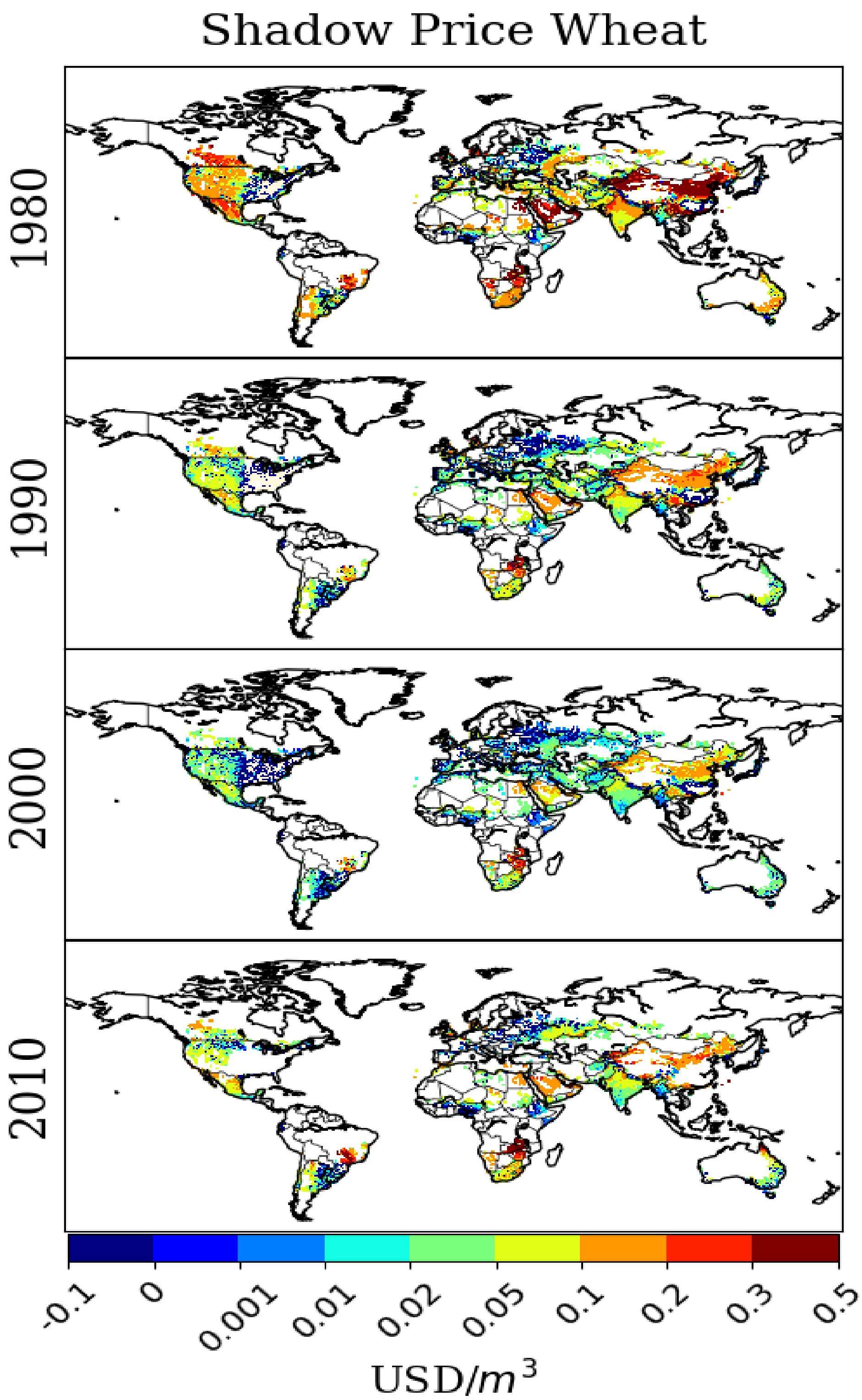


Fig 2.17. Shadow price as the economic value of irrigation water for wheat.

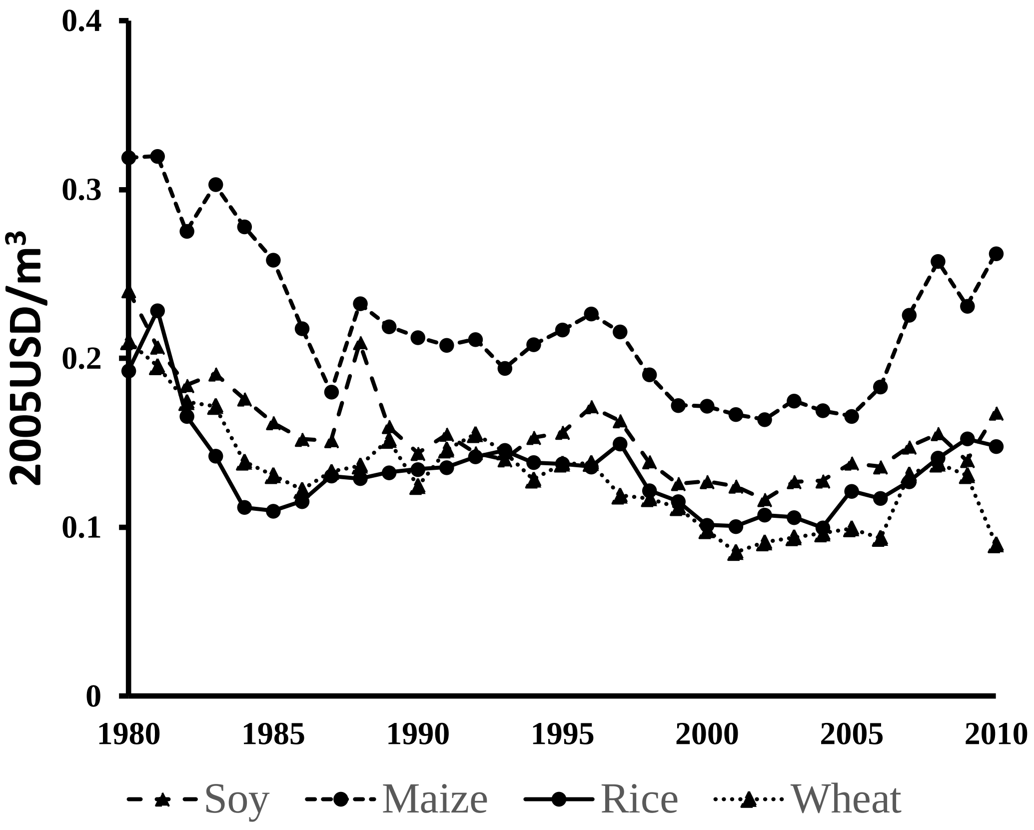


Fig 2.18. The global annual average of the shadow price of water (2005USD/m³) for different crops.

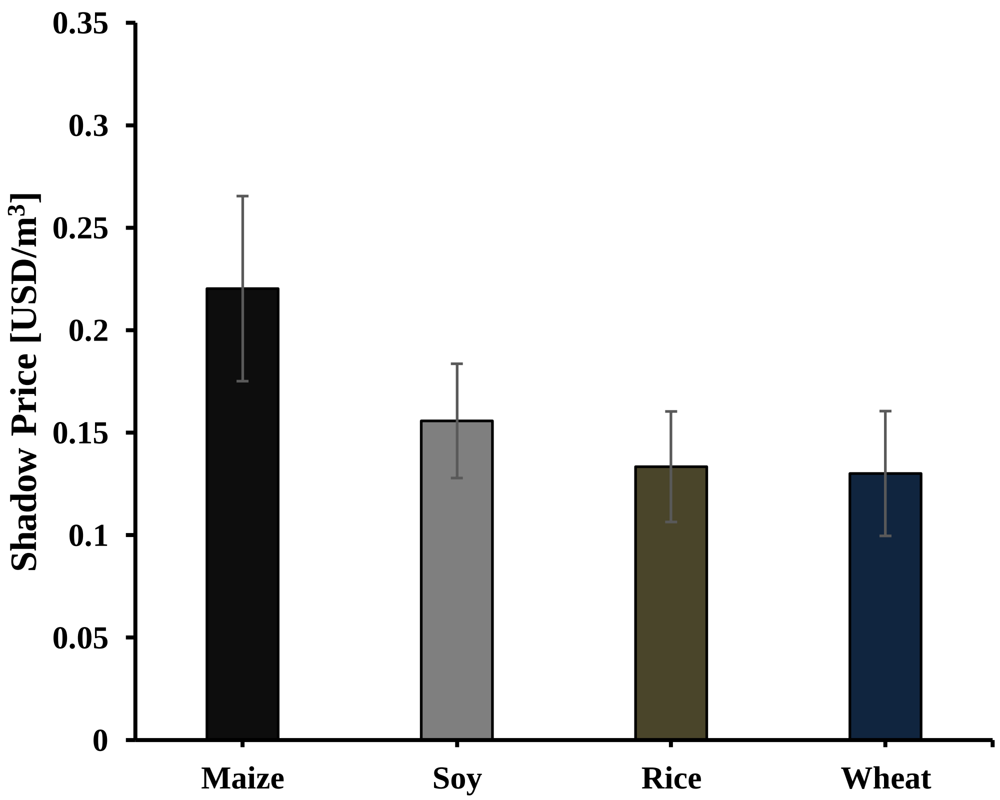


Fig 2.19. The global average of shadow price from 1980 to 2010 (2005USD/m³) for different crops.

In terms of global annual average shadow price (figure 2.18), maize has the highest value, and wheat has the lowest value (before 1990, rice is the lowest one), although it is almost at the same level as rice. The trend of shadow price is somehow as same as crop price's trend during the time. Except for maize, the shadow price is maximum in the same year as crop price, which is 1980 for soy and wheat, and 1981 for rice. For maize, the maximum shadow price was captured in 1981. Soy has a higher rate compared to rice, but in two years, 1981 and 2009, rice's value is higher. The shadow price increases remarkably after 2005 (for wheat after 2006); however, it decreases a little bit from 2008 to 2009. The decline in wheat from 2009 to 2010 is significant. The lowest shadow price is 0.09 USD/m³, and it belonged to wheat in 2001, and the maximum value is 0.32 USD/m³ for maize in 1981 (table 2.5).

Table 2-4. The minimum and maximum value of the global annual average shadow price (USD/m³) for each crop and related year.

	Maize		Rice		Soy		Wheat	
	Value	Year	Value	Year	Value	Year	Value	Year
Min	0.16	2002	0.1	2004	0.12	2002	0.09	2001
Max	0.32	1981	0.23	1981	0.24	1980	0.13	1980

Figure 2.19 shows the global average of shadow price from 1980 to 2010 (USD/m³). Maize has the highest value with 0.22 USD/m³, and after that, soy, rice, and wheat with the amount of 0.16, 0.133, and 0.130 USD/m³ have the highest value, respectively.

2.5 CONCLUSION

This study estimated the shadow price of water as an economic benefit of agriculture water uses for four major crops; maize, rice, soy, and wheat on a global scale from 1980 to 2010 over grid cells. Since water withdrawal in agriculture is for irrigation propose, therefore this study calculated the shadow price of irrigation water by applying the yield comparison method. This framework defined the shadow price as a potential marginal added value by irrigation. The result showed that in terms of global annual average, maize had the highest, and the wheat had the lowest shadow price with more than 50% difference. At grid-scale, shadow price varies region by region and year by year for all crops.

Shadow prices can maximize profit by providing a water allocation scheme. (shadow price in the agriculture sector is not enough for policy and decision-makers for optimization of water use profit; hence economic benefit analysis of other sectors (domestic and industry) are essential) (Bierkens et al., 2019).

In this analysis, we did not consider social or cultural aspects, since one product may have a low economic value, but it is culturally valuable. This study neglected all costs in both irrigation and rainfed due to a lack of information. Also, irrigation water withdrawal in this study is potential, not actual. The potential term didn't concern about the availability of water on the supply side. Therefore, taking into account the costs and considering actual irrigation demand can increase the reliability of this analysis.

Although still a lot of space to fill in this research, it is a first step to start understanding the economic value in water resources and also how utilizing this term in the sustainable development of an integrated water resource system. The recommendation for future work is to apply another production feature (Cobb-Douglas), partitioning water use component (surface and groundwater) (Bierkens et al., 2019), and expand estimate for the future.

Chapter 3: Industry

3.1 INTRODUCTION

Water in the industry is used for a variety of purposes, like transportation, cooling, manufacturing products, or as an ingredient in a final good (Shiklomanov, 2000). Also, water plays an essential role in the extraction of primary energy and biofuel appear as virtual water for irrigation water requirement of biofuel crops (Wada et al., 2016).

The primary water user in the industry sector is thermal and nuclear power plants, which require a large amount of cooling water for electricity production. Industrial water withdrawal volumes are quite different, depending on the manufacturing process technology, not only for individual branches of the industry but also within each type of production. Climate conditions are a vital factor, as well (Shiklomanov, 2000). Industrial water withdrawal appears to be significantly lower in the northern regions than in the southern areas with higher air temperatures (Shiklomanov, 2000). 19% of global water withdrawal is industrial water (FAO, 2016a). Although it is crucial, globally available data and scenarios are limited (Hanasaki et al., 2013a). Some studies tried to estimate industrial water withdrawal (IWW). Mainly IWW estimation is divided into two parts; Manufacturing and electricity production water use. Alcamo et al. (2003a) developed the hyperbolic equation model for IWW. They considered industrial water withdrawal as a function of GDP per capita. Shen et al. (2008) followed the same method, and he included total primary energy as a function of GDP. Vassolo and Döll (2005), for the first time, developed a methodology for estimation IWW at both manufacturing and electricity production water use for around 1995. They used actual data of global power plants with the geological location for electricity production. Flörke et al. (2013) used the same method for electricity production and manufacturing water use as a function of GAV (gross value added) for nationwide from 1950 to 2010. Hanasaki et al. (2013) used a regional time series regression model for electricity production water use since they argued that there is no clear relation between socioeconomic parameter and electricity production, and also it is not accurate in the case of lack of data. Wada et al. (2011, 2014) estimated IWW for electricity production as a function of GDP.

Table 3-1 Summary of earlier industrial water withdrawal estimation studies.

Reference	Drivers	Simulation Method	Temporal resolution	Spatial Resolution
Alcamo et al. (2003a)	Electricity production	IWW as functions of intensity and technological change.	Annual	Countrywide
Shen et al. (2008)	Electricity production	Simple linear relation, with applying coefficient based on strong assumption.	Annual	Countrywide
Hanasaki et al. (2013)	Electricity production	IWW as function of linear relation between electricity production and water intensity.	Annual	Regional
Flörke et al. (2013)	Electricity production and Manufacturing	IWW as function of 1. Electricity production of global power plants 2. Manufacturing water use based on gross value and technological change.	Annual	Global
Wada et al. (2011, 2014)	Electricity production	IWW as function of GDP for electricity production using (Shiklomanov 1997; Vörösmarty et al., 2005) data.	Annual	Global

Table 3.1 summarizes earlier industrial water withdrawal modeling studies (Nazemi & Wheater, 2015a, 2015b).

Although the industrial sector has a massive impact on our economic but economic value of water use in this sector is still unknown, and the same as the domestic sector mostly neglected from water resource analysis. Industrial activities have a direct impact on our GDP through goods and energy production and or transportation. The industry sector can help with water productivity. It can reduce water stress in the water-scarce region with desalination, groundwater extraction, or water treatment. There is an argument that this kind of solution is not sustainable and environmentally friendly, because these solutions are energy-intensive; therefore, they can cause high emissions of greenhouse gases, but desalination is one of the first solutions in a water-scarce area. Applying desalination technology is continuing to grow, and thermal desalination is expanded from small to large scale for decades (Haddad, 2013). It is estimated that almost 8770 desalination plants with a capacity of 16 BGD (billion gallons per day or 60 m^3) operated worldwide in 2013, and their size increased 27 times from 1995 (Ziolkowska, 2015a).

Understanding economic value in the industry sector is essential, and it can help policymakers to build-up a sufficient decision of investment and water allocation policy that directly affect human and environmental life. Since there is no big scale or global assessment of the economic value of IWW, this study tried to estimate the economic value of IWW on a global scale from 1980 to 2010 with a unique methodology with following earlier study IWW estimation.

3.2 OBJECTIVE

This study tried to investigate the economic value of IWW at global scale from 1980 to 2010. Since electricity production is the significant water use in the industry sector, so it assumes that all IWW belongs to electricity production. The objectives of this study are:

1. Quantity estimation of industrial water withdrawal in the country from 1980 to 2010.
2. Evaluation of the economic value of industrial water withdrawal. At the same spatial and temporal scale.

3. We are assessing the impact of hydropower and renewable energy on the IWW economic value from 1980 to 2010.

3.3 METHODOLOGY

Figure 3.1 shows the flowchart of the calculation procedures of IWW and also economic benefits related to IWW.

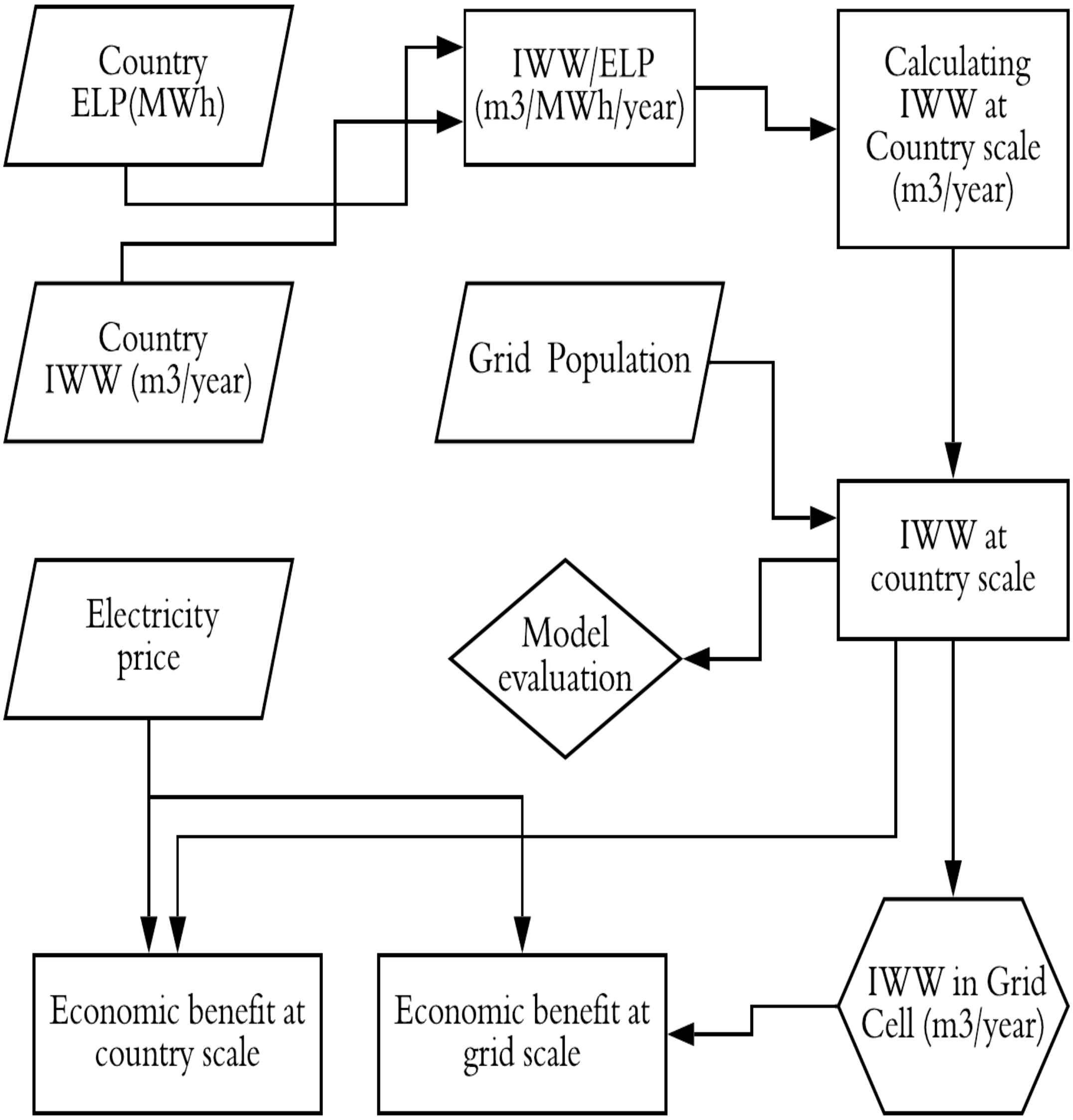


Fig 3.1. Flowchart of IWW and its economic value calculation process with input data.

3.3.1 Datasets

Electricity production data (EPL)

Electricity production data is indirectly obtained from World Bank, and it is publicly available (https://data.worldbank.org/indicator) from 1960 to 2015 at the country scale (The World Bank, 2019b), although only for few countries (mostly developed), it is available before 1971. Indirect means there is no direct data of ELP, but it is possible to obtain from other datasets. For these, two datasets are collected:

- Electricity production from a renewable source, excluding hydroelectric (kWh)
- Electricity production from a renewable source, excluding hydroelectric (% of total)

After collecting this data with a simple calculation, electricity production data can obtain:

$$ELP\ (\text{kWh}) = \left(\frac{ELP(renew\ kWh)}{ELP(renew\ \%)}\right) \times 100 \qquad 3.1$$

Since in some countries, ELP data isn't available; therefore, country electricity consumption (ELC) information is collected from the same source:

- Electric power consumption (kWh per capita)

$$ELC\ (\text{kWh}) = ELC\ (\text{kWh per capita}) \times POP \qquad 3.2$$

POP is The World Bank country's population data. For countries that ELP are not available, ELC is used instead. The global average difference between ELP and ELC is 5%. Finally, hydropower and renewable energy effect are removed for calculating industrial water intensity:

$$ELP_{nuc}\ (\text{kWh}) = ELP(nuclear\ \%)\ \times\ ELP_{tot} \qquad 3.3$$

$$ELP_{fos}\ (\text{kWh}) = ELP(fossil\ \%)\ \times\ ELP_{tot} \qquad 3.4$$

$$ELP_{tot} = ELP_{nuc} +\ ELP_{fos} \qquad 3.5$$

Where ELP_{nuc} (kWh) is electricity production by nuclear power, and ELP_{fos} (kWh) is electricity production by fossil steam.

Industry Water Withdrawal Data (IWW)

Country scale annual industry water withdrawal data are obtained from the AQUOSTA dataset of the FAO (FAO, 2016a). AQUASTAT is the most global coverage dataset, and it is considered as one of the most reliable sources of water statistics (Hejazi et al., 2013). It is a country scale, and for 135 countries, data are collected (other countries have no data) from 1970 to 2015. Based on the FAO definition, Industry water withdrawal can be renewable resources, e.g., surface water and groundwater or fossil groundwater, agriculture drainage water, treated wastewater, or desalination water. Industry water is self-supplied and not connected to the public network, if it is connected to the public system, it is considered as a domestic sector (FAO, 2016a; Hejazi et al., 2013). Hydropower doesn't include. This study follows the FAO definition of industry water withdrawal.

Grid Population data

For the population, the center of global environmental research (CGER) data (Murakami & Yamagata, 2016) has been applied. The data are estimated by downscaling actual populations by country from IMF (international monetary fund) in 0.5 × 0.5-degree grids from 1980 to 2010. For the people in an urban area, they downscaled from countries to cities and finally to grids level. For the non-urban area population, they downscaled directly from countries to grids (Murakami & Yamagata, 2016).

Electricity Price Data

Country scale global coverage of electricity price datasets are not available. Therefore recent price data are collected from Global Petrol Prices, and it is available at (https://www.globalpetrolprices.com/electricity_prices/) (Global Petrol Prices, 2018). It contains country electricity prices in kWh/USD for 2018 (88 countries have data, and 47 countries have no data). 2018 USD is converted to 1980 to 2010 USD using consumer price index (CPI) and calculating the following equation:

$$Year\ t\ USD\ value = \left(\frac{CPI_t}{CPI_{2018}}\right) \times 2018\ USD\ value \qquad 3.6$$

CPI_t is CPI for each year from 1980 to 2010, and it is collected from The World Bank. Outputs of Eq. (3.6) are considered for electricity prices from 1980 to 2010. For countries which don't have data, global countries are grouped to regions based on the international institute for applied system analysis (IIASA) 32 macro-regions (Riahi et al., 2017), and the average price of each region is used as a price of countries without data. 32 macro-regions are as follows:

- R32ANUZ = Australia and New Zealand.
- R32BRA = Brazil.
- R32CAN = Canada.
- R32CAS = Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan.
- R32CHN = China.
- R32EEU = Albania, Bosnia and Herzegovina, Croatia, Montenegro, Serbia, Macedonia.
- 32EEU-FSU = Belarus, Republic of Moldova, Ukraine.
- R32EFTA = Iceland, Norway, Switzerland.
- R32EU12-H = Cyprus, Czech Republic, Estonia, Hungary, Malta, Poland, Slovakia, Slovenia.
- R32EU12-M = Bulgaria, Latvia, Lithuania, Romania.
- R32EU15 = Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.
- R32IDN = Indonesia.
- R32IND = India.
- R32JPN = Japan.
- R32KOR = Republic of Korea.
- R32LAM-L = Belize, Guatemala, Haiti, Honduras, Nicaragua.
- R32LAM-M = Antigua and Barbuda, Argentina, Bahamas, Barbados, Bermuda, Bolivia, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guyana, Jamaica, Martinique, Netherlands Antilles,

Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela.

- R32MEX = Mexico.
- R32MEA-H = Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates.
- R32MEA-M = Iran, Iraq, Jordan, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic, Yemen.
- R32PAK = Pakistan and Afghanistan.
- R32TUR = Turkey.
- R32NAF = Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia, Western Sahara.
- R32OAS-CPA = Cambodia, Lao People's Democratic Republic, Mongolia, Viet Nam.
- R32OAS-L = Bangladesh, Democratic People's Republic of Korea, Fiji, Micronesia, Myanmar, Nepal, Papua New Guinea, Philippines, Samoa, Solomon Islands, Timor-Leste, Tonga, Vanuatu.
- R32OAS-M = Bhutan, Brunei Darussalam, French Polynesia, Guam, Malaysia, Maldives, New Caledonia, Singapore, Sri Lanka, Thailand.
- R32SAF = South Africa.
- R32SSA-L = Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe.
- R32SSA-M = Angola, Botswana, Equatorial Guinea, Gabon, Mauritius, Mayotte, Namibia, Réunion, Seychelles.

- R32TWN = Taiwan.
- R32USA = United States of America (Includes Puerto Rico, Virgin Island).

Since no data for all countries in R32SSA-M, the average value of R32SAF and R32SSA-L is used.

3.3.2 Industry Water Use Modelling

As it is mentioned in section 3.1, there are several global IWW models. In this study, two of them will be used, and one of them will be selected based on model performance. IWW in developed countries tends to decrease with increasing GDP. Still, in developing countries, IWW is consistently high and shows less motivation to reduce. However, the actual reason is unknown, but it seems in developed countries, the amount of IWW consists of the upper portion of water use; thus, they have more motivation to reduce it (Alcamo et al., 2003). WaterGAP model (Alcamo et al., 2003) used structural change (Figure 3.2) and technological change to calculate IWW with hyperbolic function.

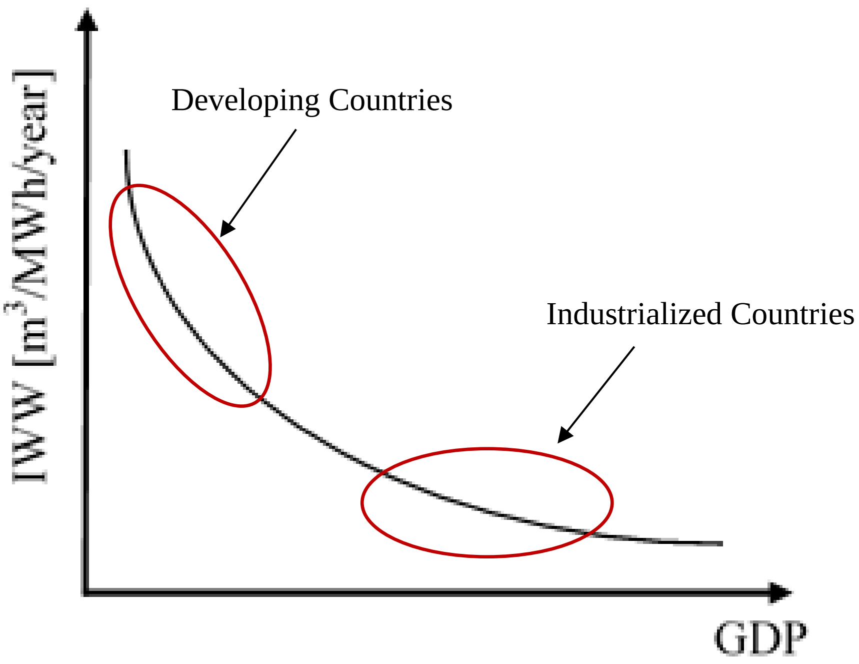


Fig 3.2. Structural change of IWW for electricity production and GDP.

This study applied the modified WaterGAP model on the country scale from 1980 to 2010:

$If\ n > 3:$

$$IWW\left(\frac{m3}{MWh}\right) = \frac{1}{\beta(GDP - GDP_{min})} + IWW_{min} \qquad 3.7$$

$If\ n \leq 3:$

$$IWW\left(\frac{m3}{MWh}\right) = \frac{1}{\beta(GDP)} + IWW_{min} \qquad 3.8$$

GDP is per person and "n" is the number of available data for each country. β is a curved parameter, and it is obtained for each country after curve fitting as same as IWW_{min}. Along with the WaterGAP model, the H08 model (Hanasaki et al., 2013a) is applied in this study. H08 model argues that, since there is no clear relation between IWW and socioeconomic parameters, therefore H08 model did not include them. Based on the relationship between IWW/ELP (m^3/MWh/year) and time (Figure 3.3), H08 model is as follow:

$$IWW(\text{m}^3/\text{MWh}) = ELP \times (I_{ind,t_0} + S_{ind} \times (t - t_0)) \qquad 3.9$$

ELP (MWh) is electricity production for each country, $I_{ind,t0}$ (m^3/MWh/year) is industrial water intensity, and S_{ind} is the slope of the linear regression of IWW/ELP (m^3/MWh/year) and time that obtained through least square method (Hanasaki et al., 2013a). t_0 is the first available data year, and it varies between countries. After applying the H08 model on a country scale, it can be distributed to a grid-scale based on population distribution.

For model performance evaluation, Willmott index of agreement (Willmott et al., 2012) is calculated at the same spatial level (Eq. 3.10):

$$d = 1 - \frac{\sum_{i=1}^{n}|Pi - Oi|}{\sum_{i=1}^{n}\left(|Pi - \overline{O}| + |Oi - \overline{O}|\right)} \qquad 3.10$$

$\boldsymbol{d}$ is Index of agreement, P_i is model-simulation values, O_i is observation values and $\overline{O}$ is observation mean. $\boldsymbol{d}$ value changes between 0 and 1, 1 indicates as total agreement, and 0 points as a complete disagreement.

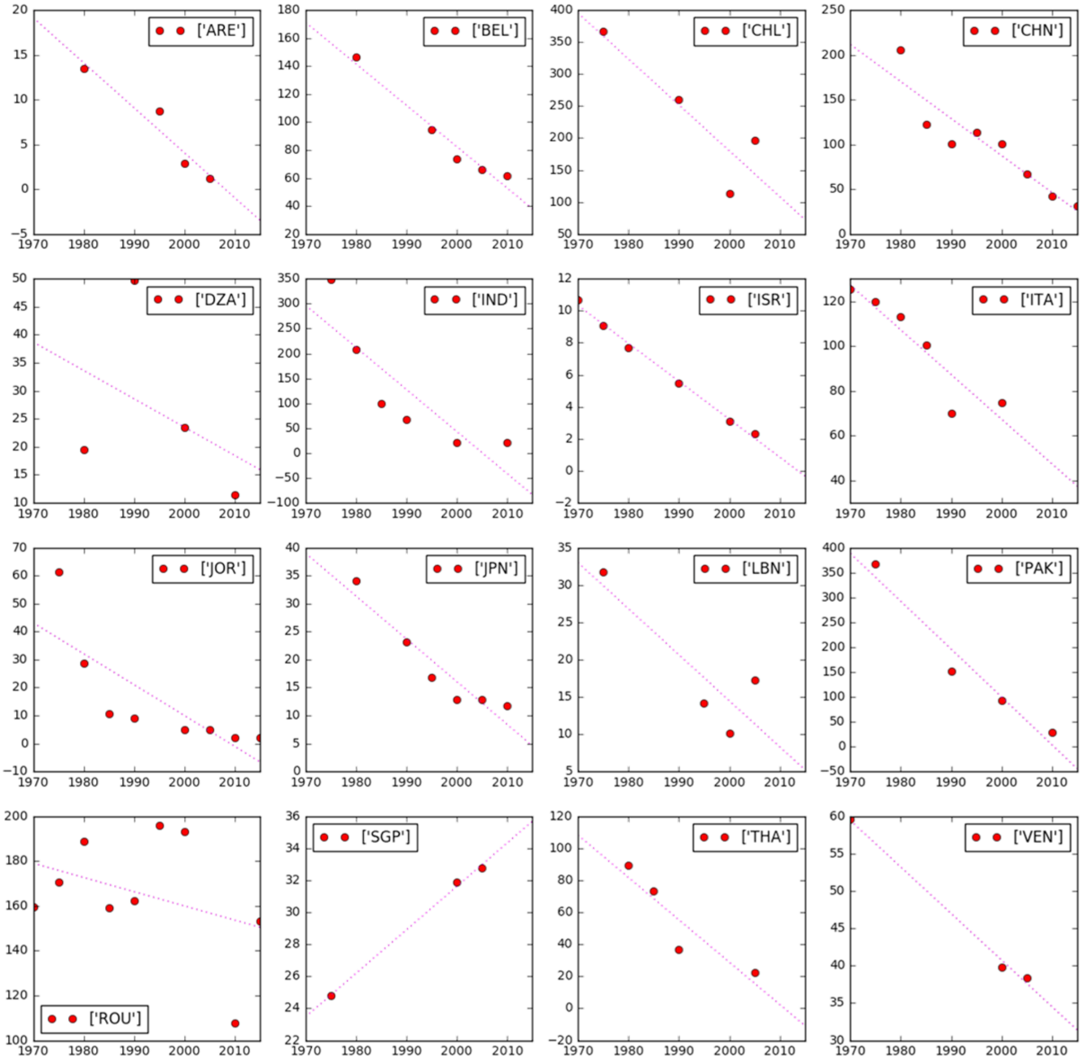


Fig 3.3. IWW/ELP (m³/MWh/year) (plot) and regressions (red dash line) in some randomly selected countries. In most countries, trends are decreasing, but in one country (SGP) is increasing.

3.3.3 Economic Benefit of Industrial Water Use

Electricity production costs can be divided into three parts. The first one direct capital cost, i.e., construction cost and material cost. The second one is the indirect cost, for example, insurance cost and the last one in operation and maintenance cost (O&M). So a lot of components are included for electricity production cost:

$$C\left(^{\$}/_{kWh}\right) = C_1 + C_2 + C_3 + \cdots + C_n \qquad 3.11$$

Water appears in O&M cost; therefore, part of the electricity generating benefit is related to water, and it isn't logical that multiple electricity prices to IWW and consider as an economic benefit of industrial water.

Desalination is energy-intensive and high-cost technology. Also, desalination cost the same as energy production cost consist of direct capital cost, indirect cost and

O&M (Atikol & Aybar, 2005; Gude et al., 2010; Haddad, 2013; Karagiannis & Soldatos, 2008; Mathioulakis et al., 2007; Ziolkowska, 2015a). Desalination technology can be applied to seawater or brackish water for freshwater production. The cost of desalination depends on the amount of water, type of water, and kind of desalination technology (Gude et al., 2010; Haddad, 2013; Ziolkowska, 2015a). Figure 3.4 shows that the cost of water production has a linear relation with energy cost (Ziolkowska, 2015a) (TDS of water between 1000 and 55000).

Based on this information, the economic benefit of industrial water use in this study calculates as "Difference of electricity produced by IWW with the amount of electricity needed to produce the same amount as IWW through desalination." There are several kinds of desalination technology in the world. Reverse Osmosis (RO) is the most common technology (Fig 3.5). Therefore RO (with 3000 m^3/day capacity) is selected for this study. Electrical energy demand and cost of desalination are collected from the literature (Table 3.2).

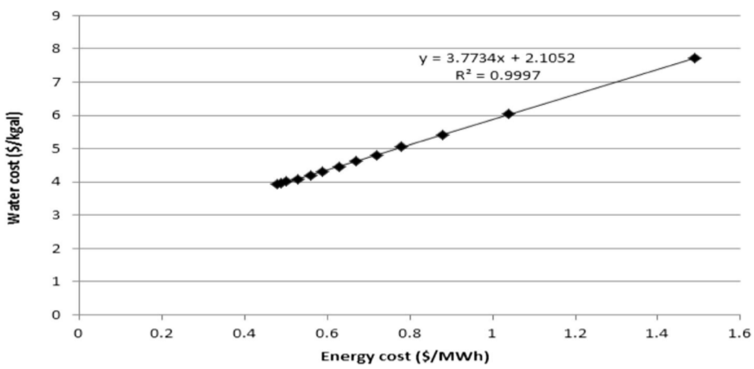


Fig 3.4. The relation between water and energy costs for water production from desalination. (Ziolkowska, 2015a)

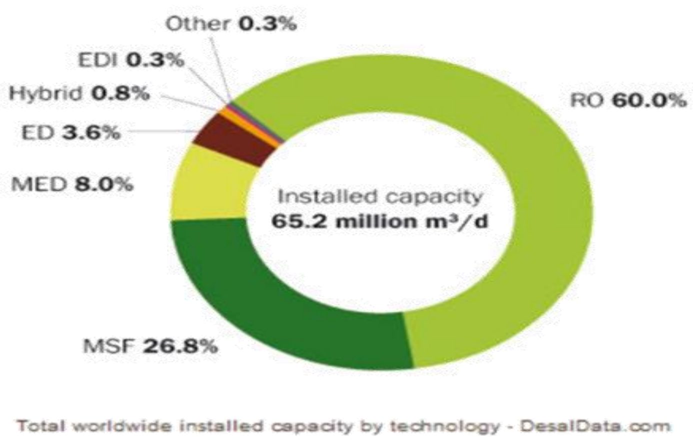


Fig 3.5. Total worldwide capacity by desalination type (DesalData.com, 2019)

Table 3-2. Electrical energy demand and cost of RO desalination from literature.

Desalination technology	Electrical energy (kWh/m^3)	Cost / Unit (USD/m^3)	Reference
Reverse Osmosis (RO)	12	1.85	Gude et al. 2010

Desalination technology is considered as reverse osmosis (RO) with 3000 m^3/day capacity

3.3.4 Calculating the Cost of electricity production

Because of the lack of data (electricity production cost is only available for the United States), the electricity production cost is calculated for the United States and then applied to all other countries. The United States electricity production cost is obtained from the U.S. Energy Information Administration (EIA) from 2007 to 2015 (for hydropower from 2010 to 2015) (EIA, 2018). As shown in figure 3.6, we correlate electricity production cost with electricity production for a different type of electricity production:

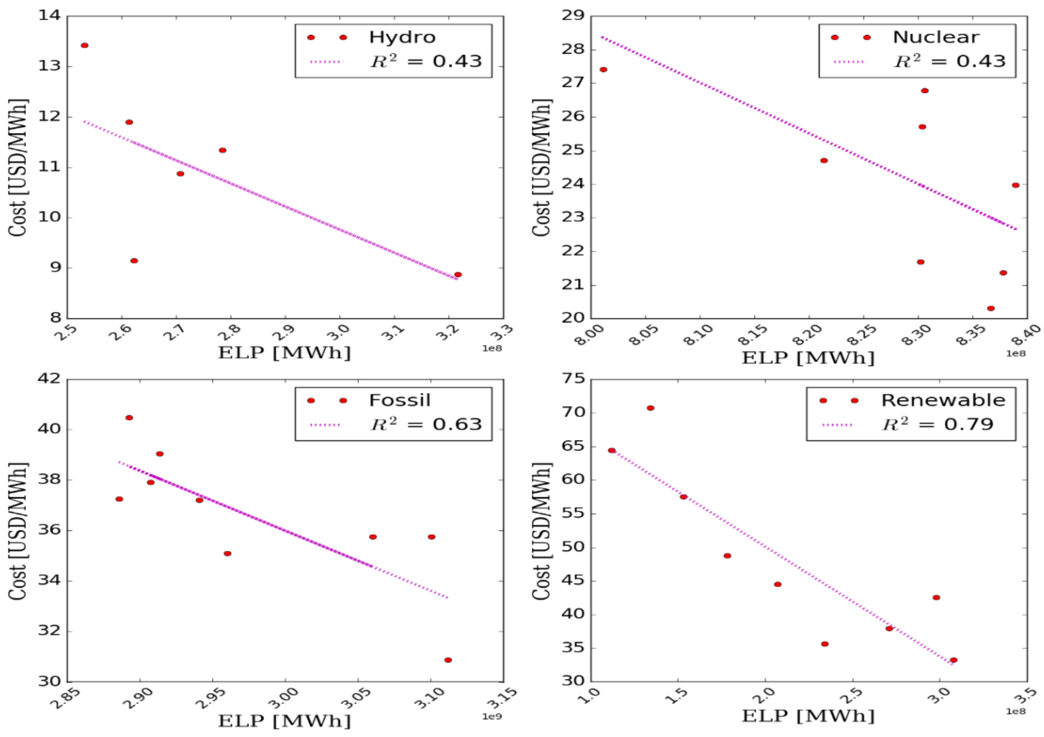


Fig 3.6. Electricity production and electricity cost correlation for the United States (X-axis is total electric production (MWh), and the Y-axis is the unit cost of the electrical production (USD/MWh)).

Since fuel price is different for countries, GDP per capita is applied to make multilinear regression between unit cost, electricity production, and GDP per capita for nuclear and fossil steam power plants:

$$UnitCost_{nuc}\left(\$/_{\boldsymbol{MWh}}\right) = -1.37 \times 10^{-7} \times ELP_{nuc} + 9.02 \times 10^{-4} \times GDPC + 97.83 \quad 3.12$$

$$UnitCost_{fos}\left(\$/_{\boldsymbol{MWh}}\right) = -2.68 \times 10^{-8} \times ELP_{fos} - 4.89 \times 10^{-4} \times GDPC + 137.65 \quad 3.13$$

Where $\boldsymbol{ELP_{nuc}}$ (MWh) is Electricity production by nuclear power, $\boldsymbol{ELP_{fos}}$ (MWh) is Electricity production by fossil steam, **Unit**$\boldsymbol{Cost_{nuc}}$ ($/MWh) is unit cost of electricity production by nuclear power, **Unit**$\boldsymbol{Cost_{fos}}$ ($/MWh) is the unit cost of electricity production from fossil steam and GDPC is country GDP per capita. The goodness of fit (R^2) is 0.67 and 0.69 for Eq.3.12 and 3.13, respectively. By multiplying electricity production of nuclear power and fossil steam to related unit cost, the total cost can be calculated:

$$Cost_{ELP}\,(\$) = Cost_{nuc} + Cost_{fos} \quad 3.14$$

- $\boldsymbol{Cost_{ELP}}$**($):** Cost of total electricity production
- $\boldsymbol{Cost_{nuc}}$ **($):** Cost of electricity production by nuclear power
- $\boldsymbol{Cost_{fos}}$ **($):** Cost of electricity production by fossil steam

By applying the cost model, the economic value of industrial water can be calculated as follow:

$$\boldsymbol{EVIWW}_{des}\left(\$/_{\boldsymbol{m^3}}\right) = \frac{(\boldsymbol{ELP_{tot}} \times \boldsymbol{Price_{ELP}} - Cost_{ELP}) - (\boldsymbol{EL}_{des} \times \boldsymbol{Price_{ELP}} - Cost_{des})}{\boldsymbol{IWW}} \quad 3.15$$

Where $\boldsymbol{EVIWW_{des}}$ is the economic value of the unit amount of IWW ($/m³), and with multiply by total IWW, EVIWW total can be calculated. ELP_{tot} (kWh) is total electricity production, EL_{des} (kWh) is electrical energy need for the same amount as IWW production from desalination, $Price_{ELP}$ ($/kWh) is electricity price, IWW (m^3) is industrial water withdrawal (calculated by model), $\boldsymbol{Cost_{ELP}}$ ($) is the cost of electricity production and $\boldsymbol{Cost_{des}}$ ($) is the cost of desalination.

3.3.5 Assessing the impact of hydropower and renewable energy on IWW economic value

Hydropower and renewable energy are excluded from the calculation of IWW; therefore, in this study, we try to assess how hydropower and renewable energy affect the economic value of IWW. If we consider these technologies, total electricity production will be increased:

$$ELP_{tot} = ELP_{nuc} + ELP_{fos} + ELP_{hyd} + ELP_{ren} \qquad 3.16$$

Along with electricity production, electricity production cost also will be increased:

$$\text{Cost}_{\text{ELP}}\,(\$) = \text{Cost}_{\text{nuc}} + \text{Cost}_{\text{fos}} + \text{Cost}_{\text{hyd}} + \text{Cost}_{\text{ren}} \qquad 3.17$$

Since IWW doesn't change, by replacing ELP_{tot} *and* Cost_{ELP} in Eq.3.15, the economic value of IWW that includes hydropower and renewable energy can be calculated. For electricity production cost of these two power plants, linear regression model, which are derived from figure 3.6, are considered:

$$\boldsymbol{UnitCost_{hyd} = -5 \times 10^{-8} \times ELP_{hyd} + 23.51} \qquad 3.18$$

$$\boldsymbol{UnitCost_{ren} = -2 \times 10^{-7} \times ELP_{ren} + 82.77} \qquad 3.19$$

The goodness of fit (R^2) is 0.43 and 0.79 for Eq.3.18 and 3.19, respectively.

- $\boldsymbol{ELP_{hyd}}$ **(MWh):** Electricity production by hydropower
- $\boldsymbol{ELP_{ren}}$ **(MWh):** Electricity production by renewable energy
- $\boldsymbol{UnitCost_{hyd}}$ **:** Unit cost of electricity production from hydropower
- $\boldsymbol{UnitCost_{ren}}$**:** Unit cost of electricity production from renewable energy

3.4 RESULT

3.4.1 Model evaluation

Water GAP and H08 model performance evaluated based on the Willmott Index agreement. Figure 3.7 shows the coefficient of determination of each model against historical observation (AQUASTAT data).

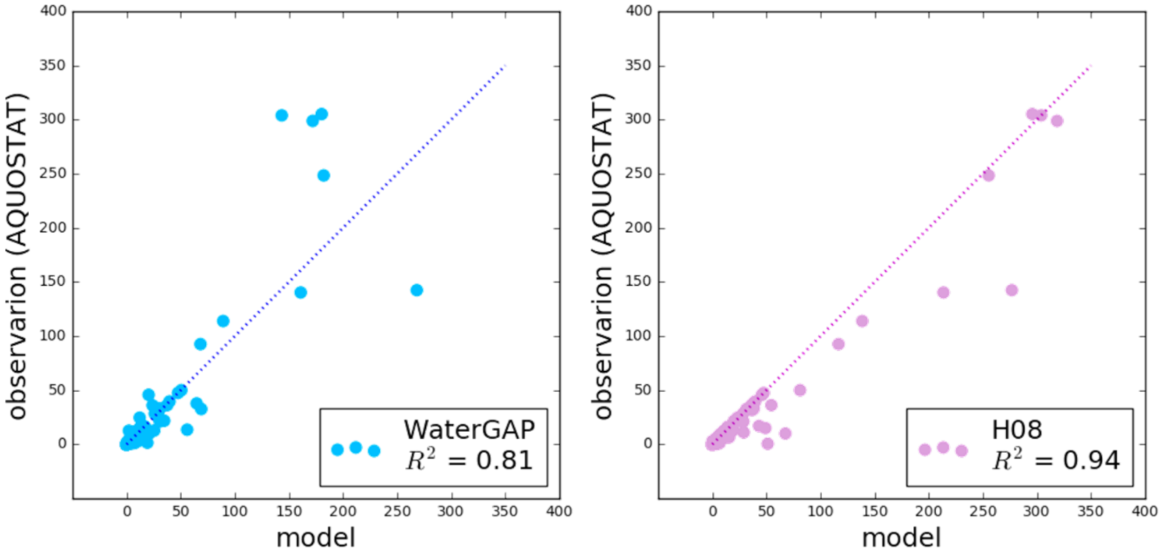


Fig 3.7. Coefficient of determination of estimated IWW of each model against historical data (AQUASTAT data). Each plot is IWW of each country in the different years from 1980 to 2010.

Both models estimated IWW very well, and the coefficient of the WaterGAP and H08 is 0.81 and 0.94, respectively. Estimation of both models in low value is good, but in a higher value, the H08 shows more overestimation.

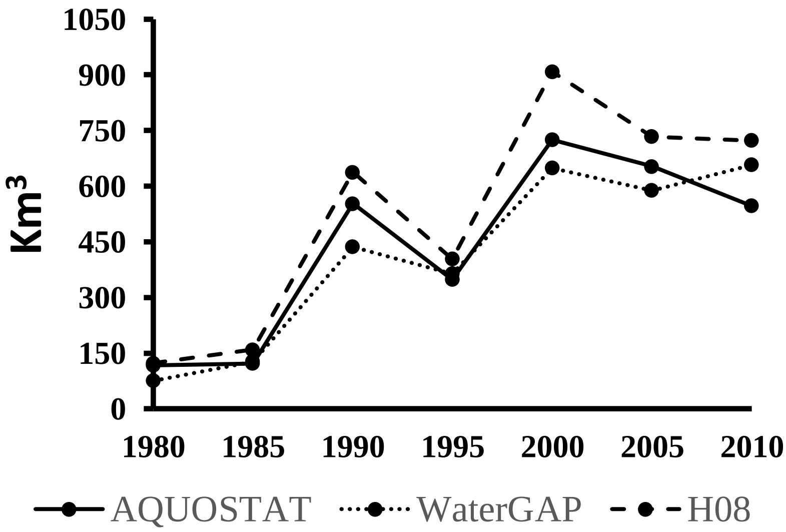


Fig 3.8. Global IWW of H08 and WaterGAP model in available historical data (AQUASTAT) from 1980 to 2010.

Willmott index of the agreement is calculated for the country scale globally. Figure 3.9 and 3.10 shows Willmott index of each model on the country scale.

The lowest value of the Willmott index for WaterGAP is Mexico, and for H08 is Cuba. The blue area in H08 is dominated, and the Willmott index value in some countries like Australia, Malaysia, and Russia is more significant than 0.8 in both models. In most of the countries, H08 has better performance, especially in countries which are historical data are more available. China and India are particular cases, although they have enough historical data (China has 7, and India has 5 data), model performance in WaterGAP is better than H08. Both models are sensitive to the number of available information (H08 is sensitive because of least square method), and WaterGAP shows the better result when the number of available data is more than three and using Eq. 3.7. WaterGAP indicates very low agreement in North America.

Wilmott index of agreement of H08 and WaterGAP model is summarized in table 3.3 (Minimum and maximum captured Willmott index and the global average value of each model performance).

Table 3-3. Willmott index value of WaterGAP and H08 model at country scale and the global average.

Model	Min Value	Max Value	Average Value
WaterGAP	0.03	1	0.51
H08	0.001	1	0.65

Regarding the Willmott index value, the Min and Max value of both models are almost the same, but in global average value, H08 model shows nearly 27% better performance than the WaterGAP model. Based on the coefficient and Willmott index, the H08 model is selected for the estimation of IWW and its associated economic benefit of water use in this study.

3.4.2 Global distributions of Industrial water Use

Figure 3.11 and 3.12 shows the global spatial distribution of IWW (km^3 per year) and IWWC (m^3/year/cap).In 1980 the United States had the highest amount of IWW, and in different regions like Western Europe and dense population areas like India and China, IWW is relatively high compared to the other areas.

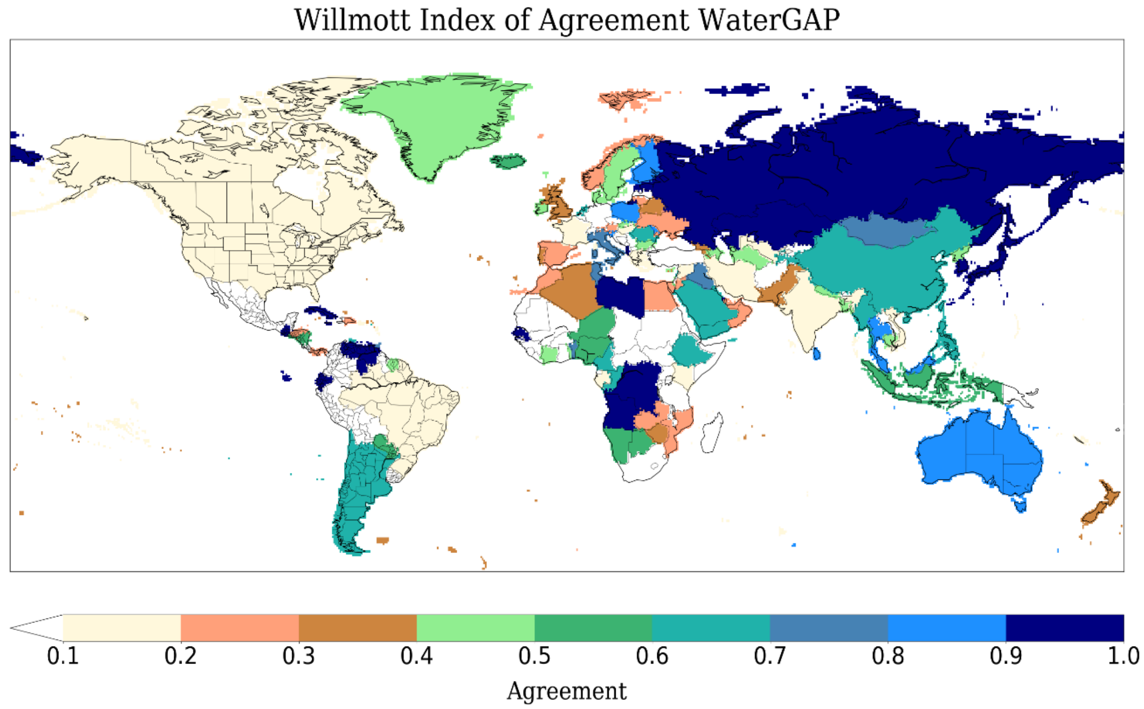


Fig 3.9. Willmott index of agreement at country scale for WaterGAP model IWW calculation.

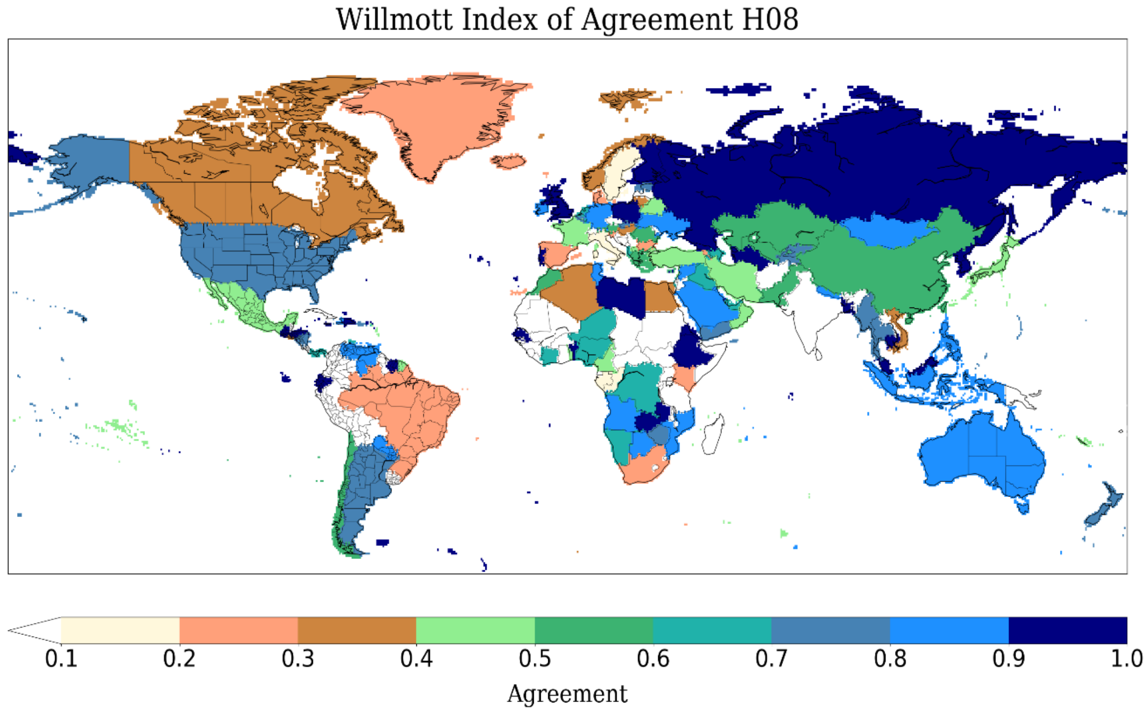


Fig 3.10. Willmott index of agreement at country scale for H08 model IWW calculation.

In general, IWW changes during 30 years are small and stay at the same level in most of the global regions; for example, in the African area despite the increasing population, IWW almost remain constant during 30 years from 1980 to 2010.

In China and India, due to both population and economic wealth growth, as a result, IWW continues to grow until 2010. The United States had the highest amount and kept this high amount for 30 years. In 2010 in some countries, mostly in Europe, IWW is decreased. It could be a sign of the increasing efficiency of industrial water use in these countries.

In the IWWC, three trends are captured. The first one is some countries that IWWC tends to decrease mostly in European countries; the second is almost stays at the same level for 30 years, i.e., India, United States, Canada, and countries in South America region. In these two groups, IWWC is decreased, or the growth rate of IWW is lower than the population growth rate. The last one is, countries that IWWC is increased, mostly in African countries and Australia and China. In these countries, IWW is increased, and maybe the growth speed of IWW is higher or the same as the population.

Figure 3.13 shows industrial water withdrawal distribution in a grid cell from 1980 to 2010. Since the ecological location of electricity production of power plants are unknown, therefore grids location is not actual water used place, but they can be considered as a potential place. In 1980 in some areas in the United States and Western Europe, IWW is high. The United States almost keeps the level of water use, but in Europe, trends are decreasing, especially in 2010. IWW expansion in China is very substantial. IWW is very low in Africa, and just near the Nile River and some parts in Nigeria and South Africa, IWW is insignificant. In South America, water use in coastal lines in Brazil and Chile is remarkable. Australian water use doesn’t show significant changes and remains almost the same level for 30 years.

In the coastal area and population dese area like big cities, the amount of IWW is high, and in 2010 mostly in developed countries, IWW declines. It can be because of efficiency increase due to technological improvement, but also the global economic recession around 2008 can be one of the reasons.

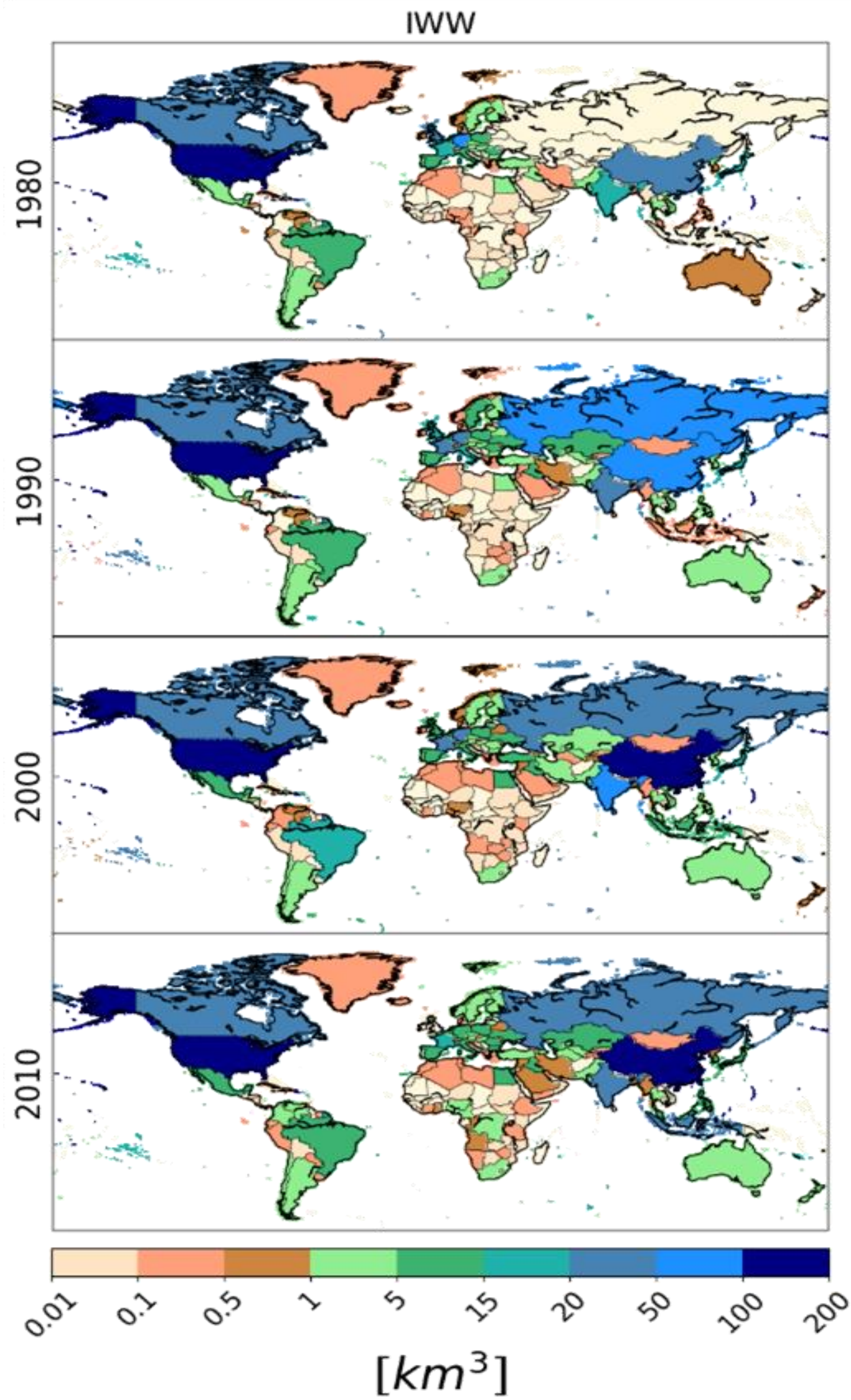


Fig 3.11. Global distribution of IWW (km³/year) at country scale.

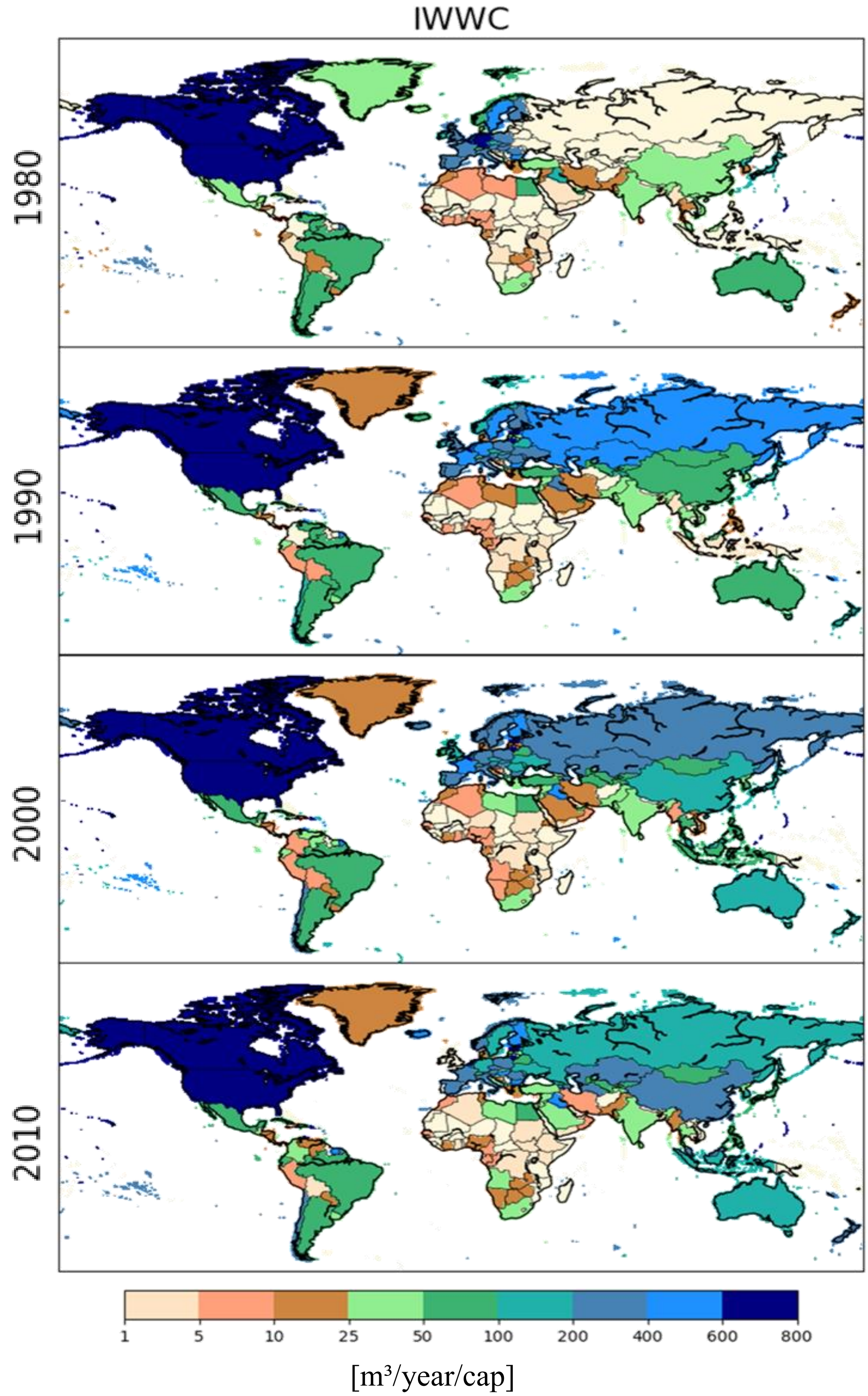


Fig 3.12. Global distribution of total IWWC (m³/year/cap) at country scale.

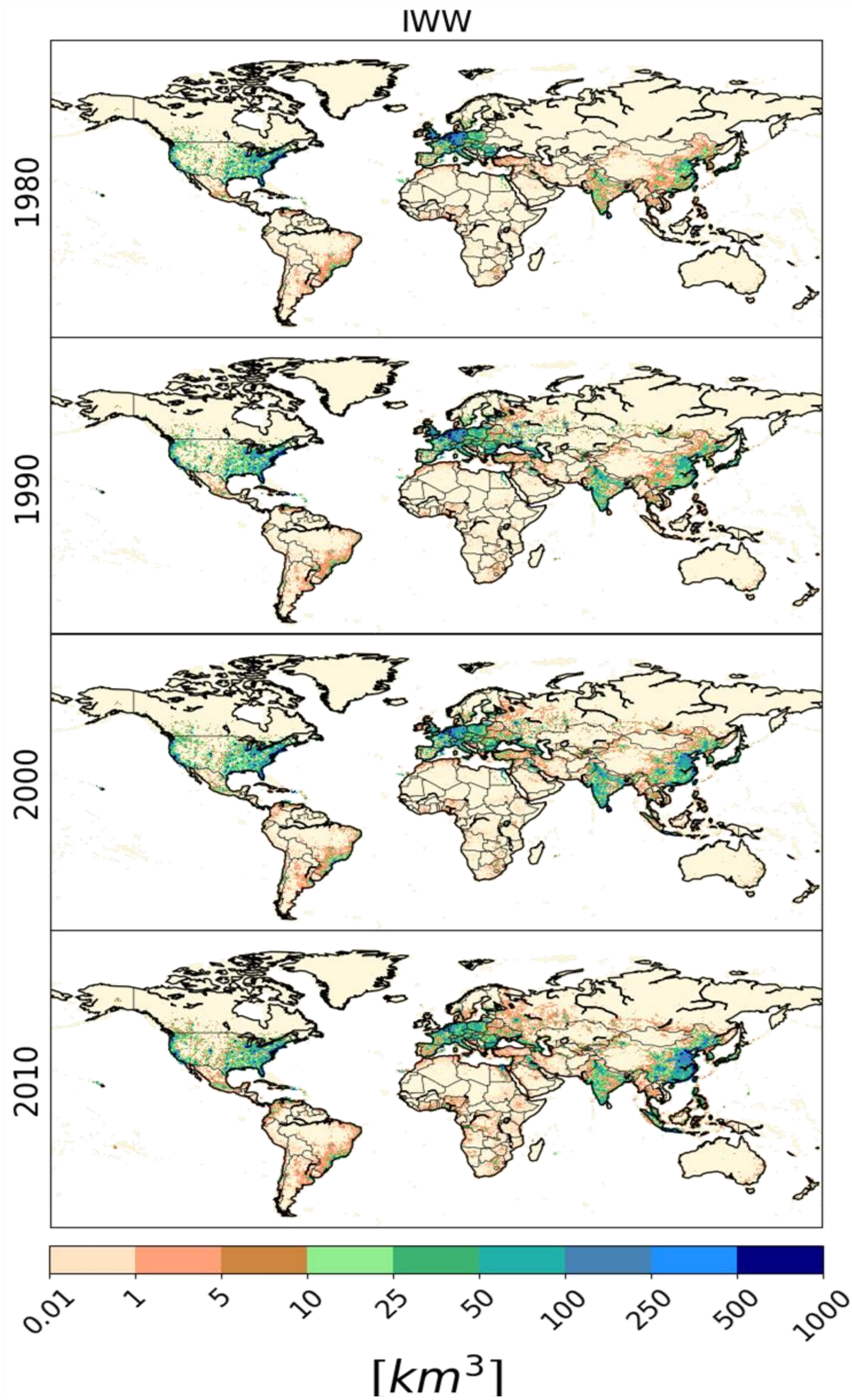


Fig 3.13. Global distribution of IWW (Million m³/year) at grid scale. Only grid cells which have more than 5000 inhabitants are considered.

Global IWW increases 1.5 times in 2010 compared to 1980; it means the average annual growth rate is 1.7%. In continental-scale, IWW increases 4.7, 4, 4.1, and 1.5 times with a yearly average increase of 12.3, 10, 10.4, and 1.8 % for Africa, Asia, Oceania, and South America, respectively. Also, IWW is decreased 0.87 and 0.93 times, with an average annual decrease of -0.4 and -0.2 for Europe and North America, respectively (Figure 3.14). Africa has the highest, and Europe has the lowest growth rate of IWW.

Global electricity production increases 3.2 times and 3.9, 7.8, 2.2, 1.9, 2.9, and 4.2 times for Africa, Asia Europe, North America, Oceania, and South America continent, respectively (Table 3.4). It is noticed that in all continents except Africa and Oceania, the IWW growth rate is lower than the ELP growth rate. For Africa and Oceania, it can refer to change ELP policy and applying more water-intense power plants. In Europe and North America, IWW decreases, since ELP increases at the same time. It indicates in the continents with more developed countries; water use efficiency is increased in the industrial sector due to technology improvement. In general, IWW growth is lower in developed continents compared to continents with a high number of developing or least developed countries.

In terms of Industrial water use intensity (m^3/MWh/year) (Figure 3.15), the global amount is halved for 30 years. In Africa and Oceania, the IWW intensity trend is increasing, and for others, trends are decreasing. Reduced amount in Europe and North America is substantial since in 2010 IWW intensity is almost 40 and 50% of 1980 in Europe and North America respectively and can be an excellent example of increasing water use efficiency.

Table 3-4. ELP (million MWh) at the continental scale.

Continent	1980	1985	1990	1995	2000	2005	2010
Africa	134	192	237	274	350	451	522
Asia	954	1291	2023	2851	3804	5356	7398
Europe	1672	1963	3505	3245	3495	3832	3758
North America	2331	2566	3116	3524	4123	4396	4409
Oceania	84	112	146	162	203	224	243
South America	68	73	86	99	152	193	283
Global	5243	6197	9113	10156	12128	14451	16612

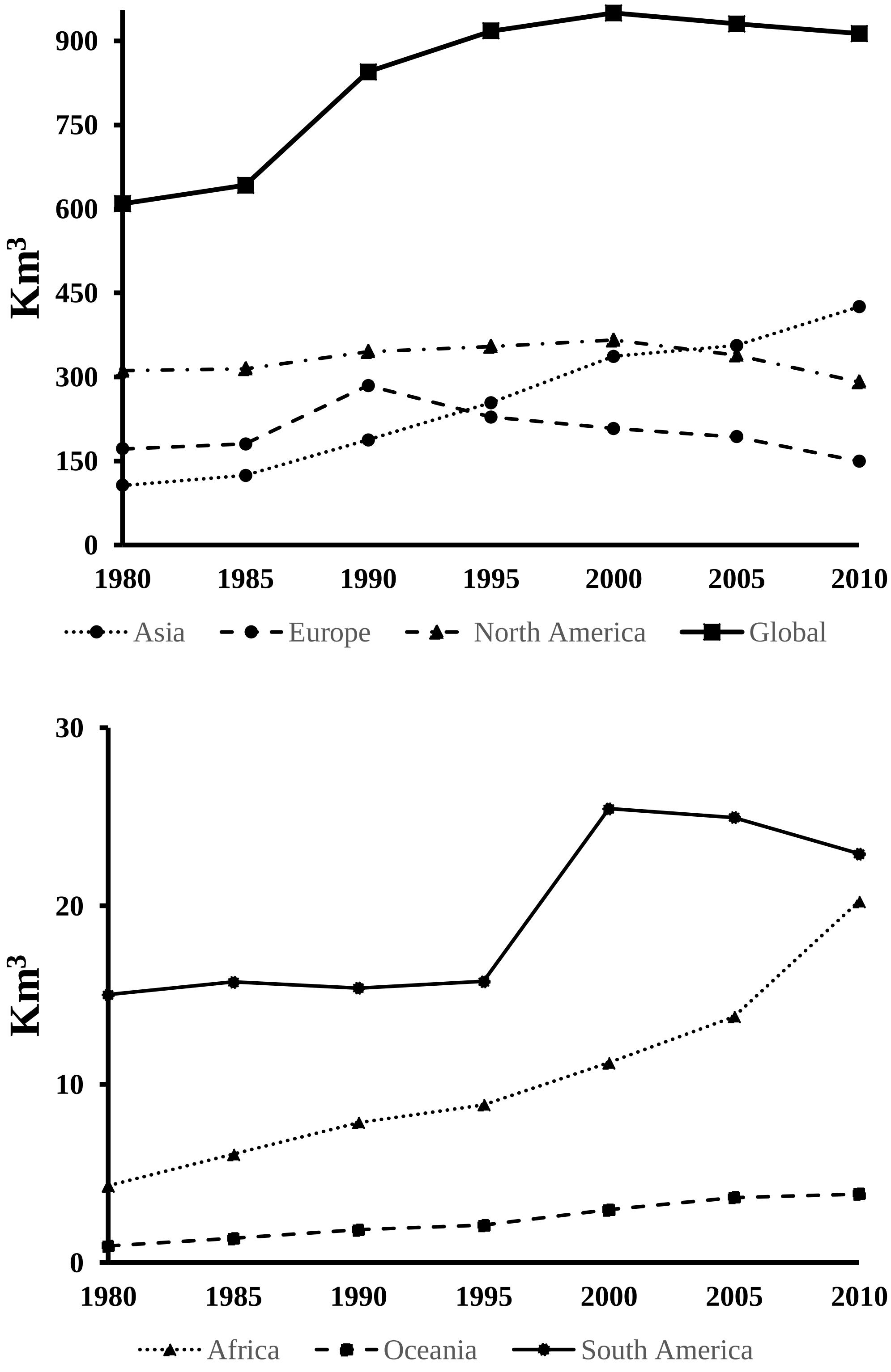


Fig 3.14. IWW (km^3/year) at different Continents (Paraguay is excluded from IWW calculation since it has a very high value in 1995 (54.6 km^3)).

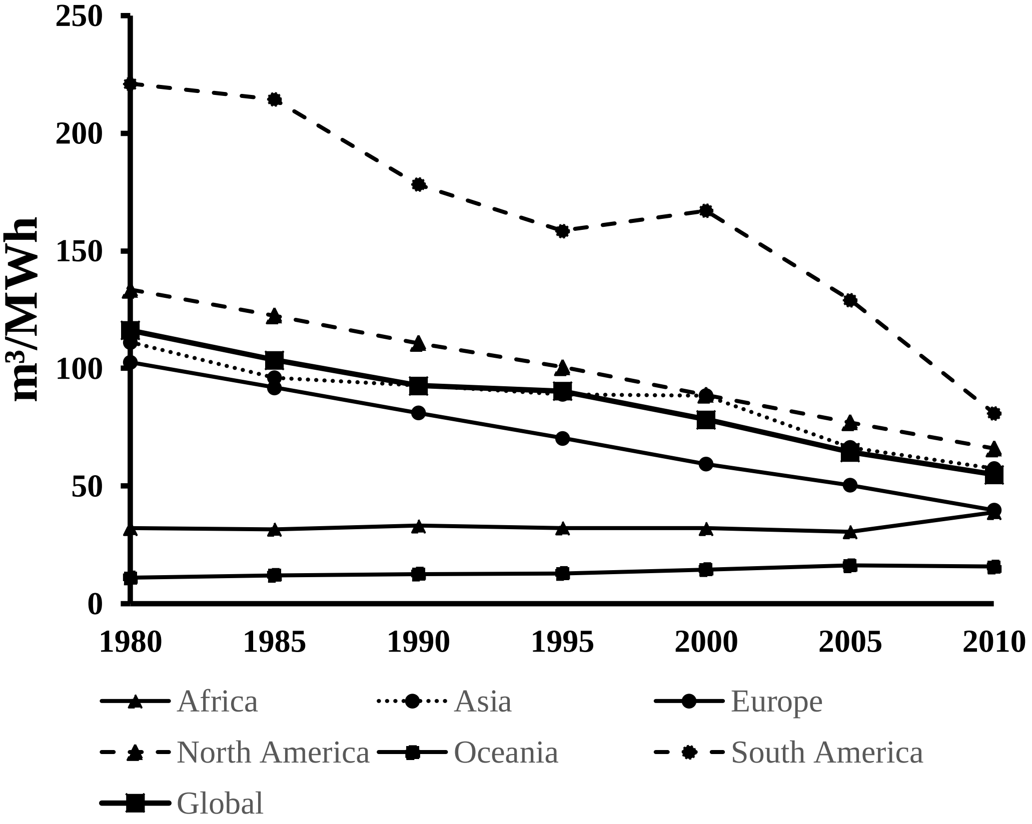


Fig 3.15. IWW intensity (m³/MWh/year) at the continental scale.

3.4.3 Economic Value of Industrial Water Use

The economic benefit of water use in the industry sector is calculated based on section 3.3.3 methodology.

Figure 3.16 shows the average electricity price for 30 years for each continent. Oceania has the highest and Africa, and Asia are almost at the same level, and they have the lowest price.

In terms of economic value (figure 3.17), in 1980, most of the country's economic value is negative or very small, and this trend continues until 2000. Although in 2000, still in some countries like Mexico and Iran, economic profit is negative. It seems after 2000, RO technology becomes more feasible worldwide. In 2000 the economic value of most countries became more than 0.1 USD/m³. China and The Unites Stae's economic value is higher than 1 USD/m³ from 1980. It is noticed that in some African countries like Congo, economic value is higher than 1 USD/m³. Along with developed countries like Japan or Western European countries, the IWW value is also high in Australia, Brazil, and India. In general the economic value of IWW high in tow kinds of nations, one in the country that although electricity production is not the highest, the price of electricity is high, like Australia. The second group is a country that produces a high amount of electric power, such as India. In the Middle East, economic value is continuously negative for 30 years in most regions. It seems in these countries since a lot of resource for electricity production is available, the price of energy is low, and as a result, economic value is also low. It could be one of the reasons that this region is the densest area in terms of the number of desalination plants. In the highest electricity producer countries, the United States and China, economic value is lower compared to other developed countries. It can be referred to as considering only electricity production in this study. Including the manufacturing sector can increase the economic value in countries which have a high contribution of manufacturing, i.e., China, Japan, Some European countries or the United States (In Japan and Germany, since electricity price in higher than China or the United States, the economic value is also higher).

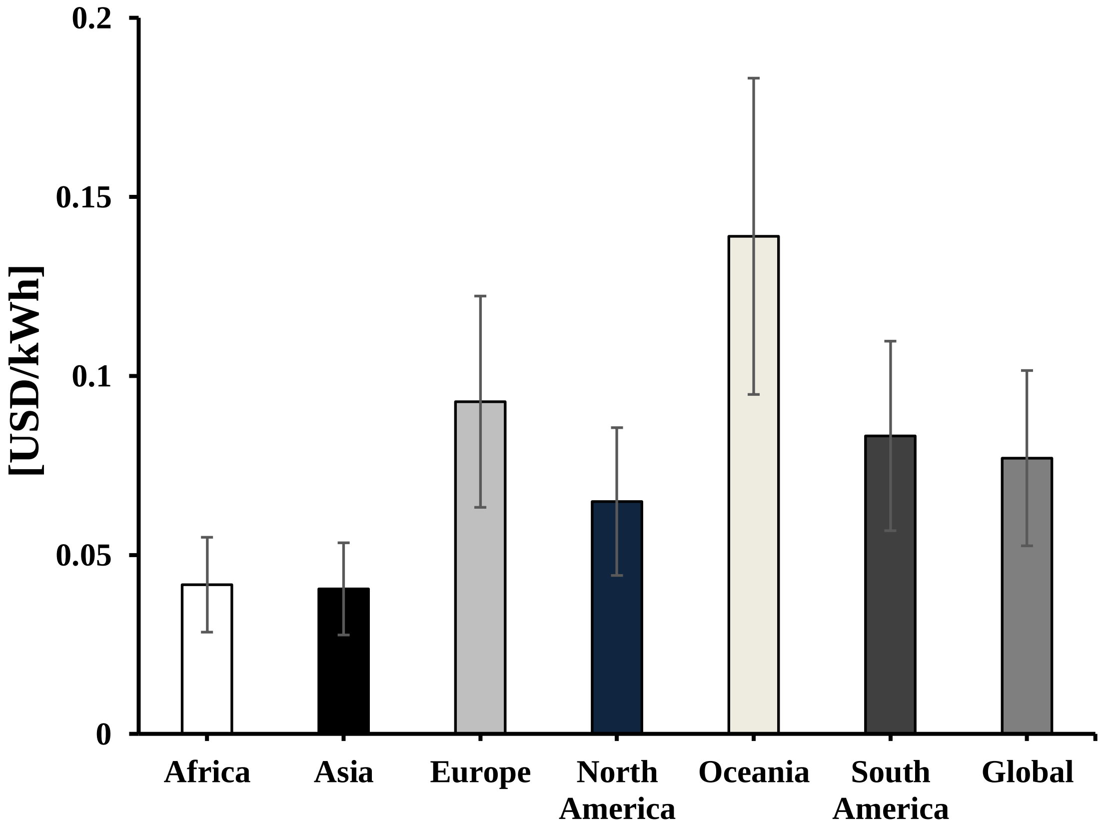


Fig 3.16. Average electricity price at the continental scale from 1980 to 2010.

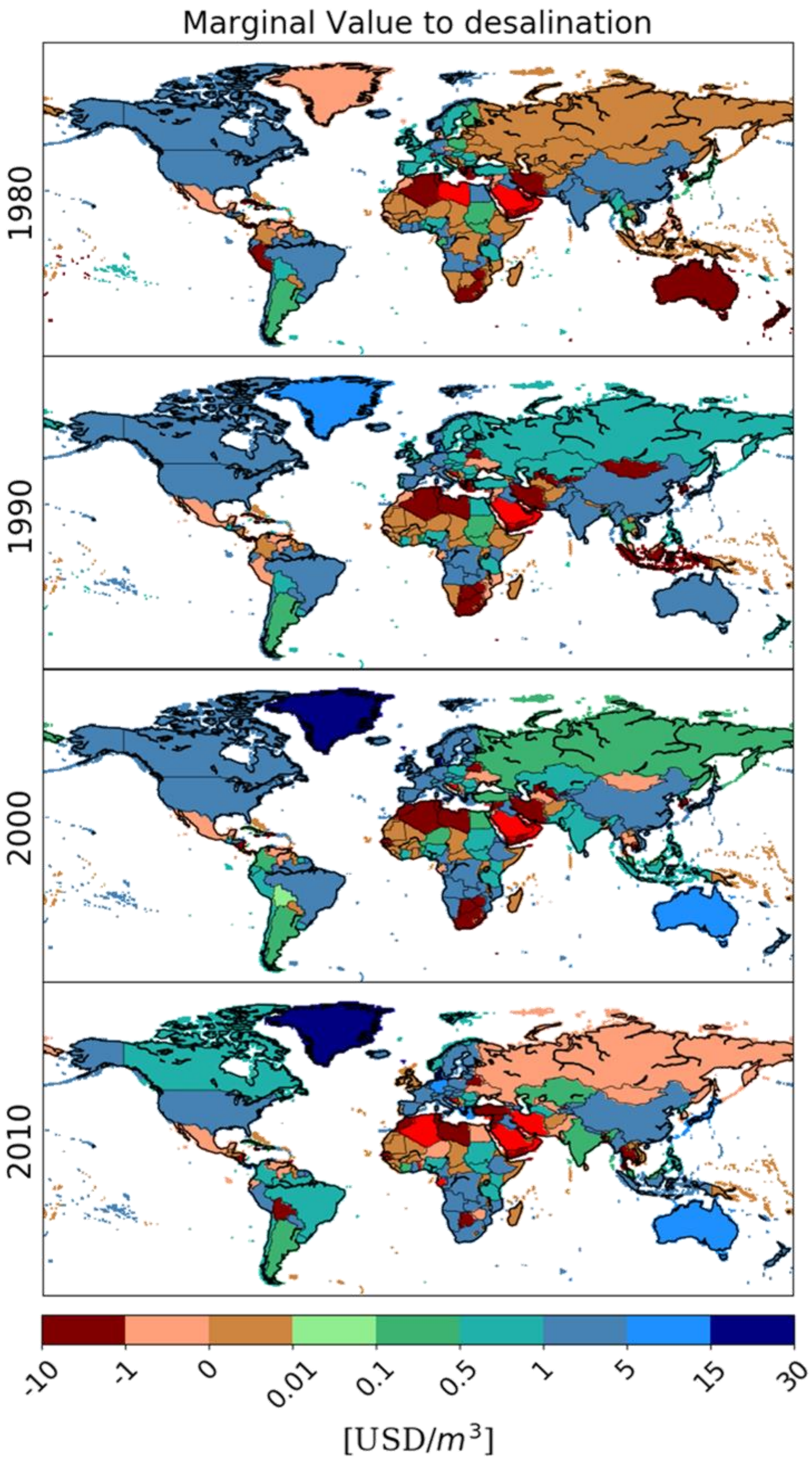


Fig 3.17. The economic value of IWW (USD/m³) at country scale.

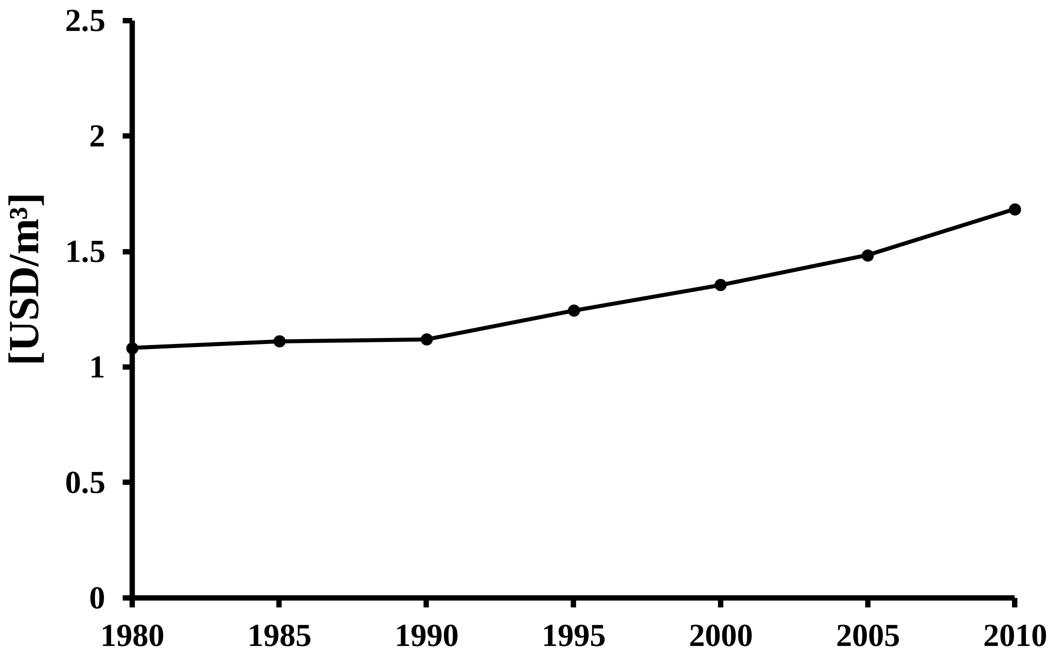


Fig 3.18. The global average of IWW economic value (USD/m³) from 1980 to 2010.

The global average of IWW economic value is increased 1.6 times during 30 years from 1980 to 2010 (figure 3.18). The annual average growth rate is 1.9%. From 1980 to 1990, the water value remains almost at the same level, but after that, it starts to overgrow until 2010.

On the continental scale (table 3.5) in all continents, economic value is increasing except for South America. Water value increases in Oceania are substantial, and it is increased by more than 400%, with the average annual growth rate of 13%, since this value for Europe and North America are more than 2 and 1.6 times with almost 3.5 and 2.2% yearly growth rate respectively. Africa's economic value is negative, and it came above zero just in 2010. For Oceania, water value is negative in 1980 and 1985.

economic value, growth is higher than IWW growth, but almost at the same level of electricity production growth in Europe, North America, and Oceania. in these continents, while IWW is decreasing economic value increases. It shows the productivity of electricity consumption is increasing during the time due to technology development and efficiency growth. This kind of improvement is beneficial in case of water scarcity, and it can reduce pressure on the water resource. But for other continents, the economic growth rate is less than IWW and electric power production growth rate.

Table 3-5. Continental IWW Min and Max value (USD/m³) from 1980 to 2010.

Continent	1980	1985	1990	1995	2000	2005	2010
Africa	-1.15	-0.86	-0.52	-0.35	-0.22	-0.17	0.28
Asia	1.01	0.99	0.99	1.05	1.11	1.15	1.45
Europe	0.86	0.96	0.91	1.06	1.25	1.54	1.75
North America	1.27	1.29	1.40	1.51	1.69	1.88	2.09
Oceania	-2.37	-0.04	1.88	3.61	4.74	5.67	7.30
South America	1.11	1.05	1.00	1.34	0.84	0.79	0.77
Global	1.08	1.11	1.12	1.24	1.36	1.48	1.68

Until now, all economic value was related to the unit amount of water (1 m³). Figures 3.18 shows the total economic value of IWW (USD) on a global scale over the grid-level from 1980 to 2010.from 1980 to 2010, IWW doesn't make any profit in a lot of countries. As shown in the figure, red areas are continuously growing during the time, and in 2010, almost all middle eastern countries have a negative value. Mostly in developed countries in West Europe, The United States and Japan, the economic benefit is high. China's economic value growth is substantial from 2000 to 2010. Same as IWW, economic value in the grid is also a potential value. In general, economic value is higher in developed countries compared to developing countries. Economic value in dense population areas or big cities is also high. In Middle Eastern countries with high availability of energy resources, economic values are less than zero. As expected, in African countries, economic value is low, and North African countries' economic value is negative. Like the global average economic value of unit IWW, the global average total economic value of IWW is continuously growing up (figure 3.20). From almost 660 billion USD in 1980, it reached 1537 billion USD in 2010, and it means the economic value is increased nearly 2.3 times, with average annual growth of 4.4%.

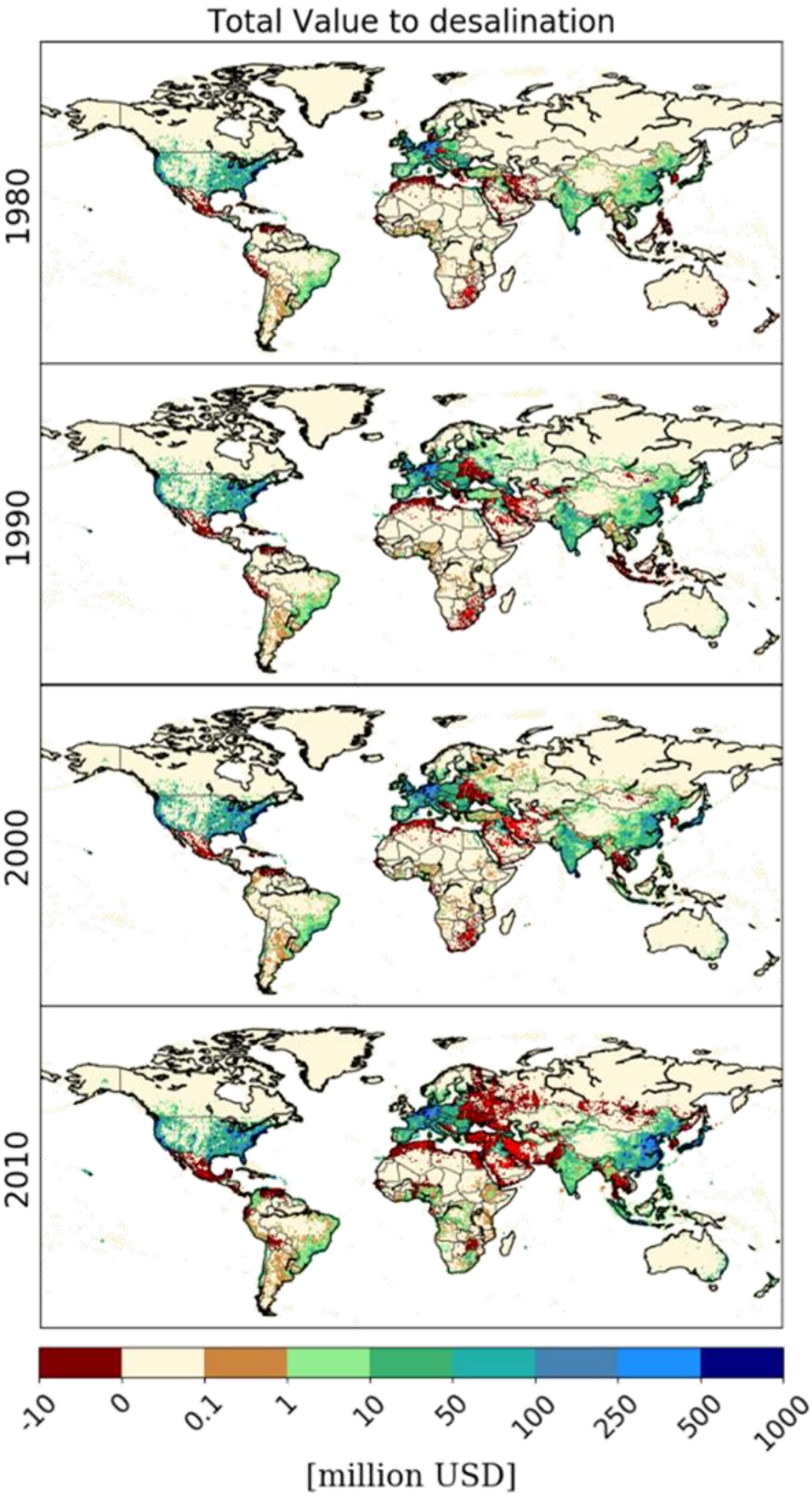


Fig 3.19. The total economic value of IWW (USD) on the grid-scale. Only grid cells that have more than 5000 inhabitants are considered.

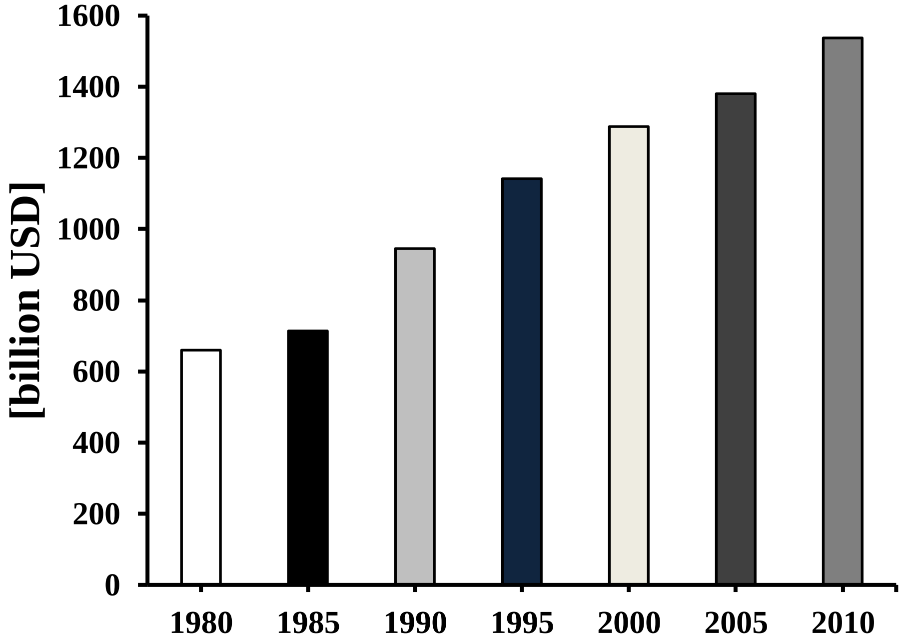


Fig 3.20. Global total economic value (USD) of industrial water use from 1980 to 2010.

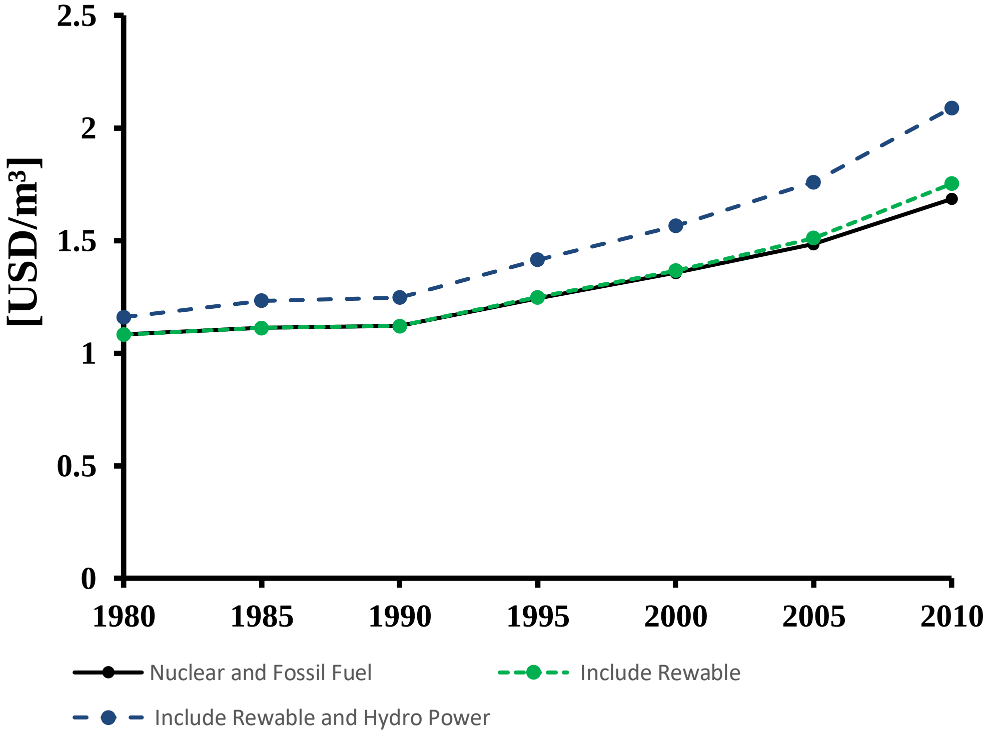


Fig 3.21. Impact of hydropower and renewable energy on economic value (USD/m^3) of IWW.

Figure 3.21 shows how hydropower and renewable energy improve the economic value of IWW. Hydropower increased 13% of the economic value during the 30 years since renewable energy just grew 1% in the same period. Hydropower has a higher share compared to renewable energy. Renewable energy is a new advanced technology, and it has not been used in a lot of countries, but it will be shared more in the future. Figure 3.22 shows the total economic benefits growth due to hydro and renewable energy use. Blue parts are added economic benefits by hydro and renewable energy. In 2010, the total economic benefits are increased by 24% and reach nearly 1900 billion USD by considering hydropower and renewable energy.

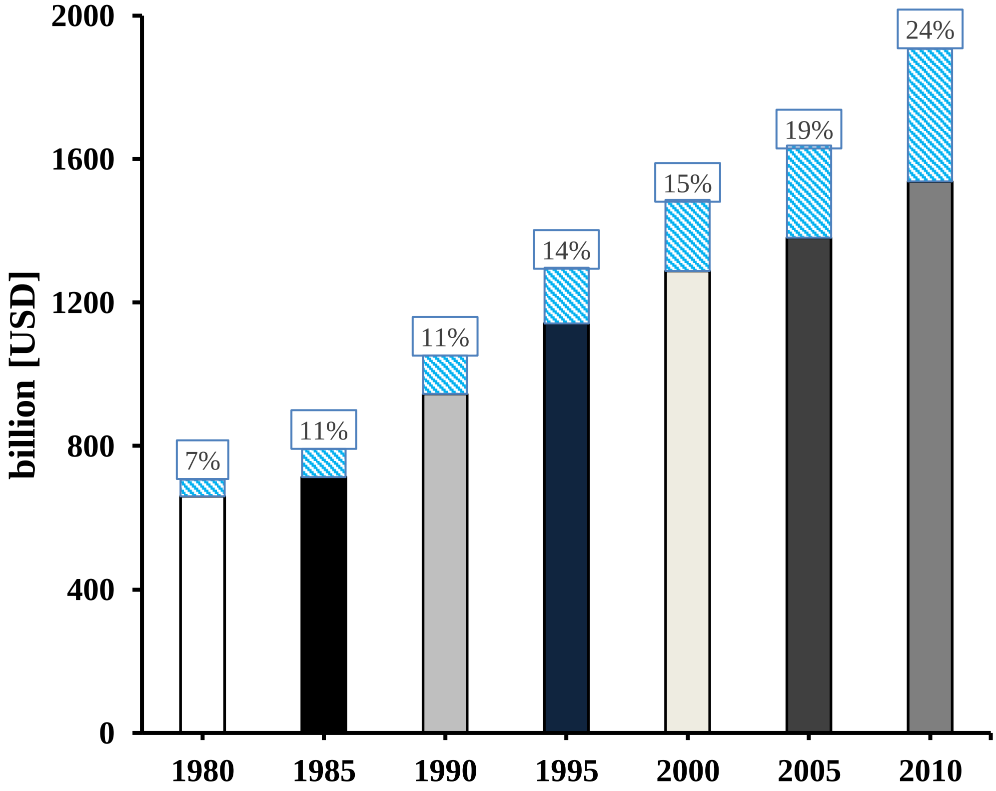


Fig 3.22. The total global economic benefits added by hydropower and renewable energy (USD) (blue area).

The application of hydropower and renewable energy has a different impact on the country scale. As shown in figure 3.23, in some countries like Canada, South America, and African countries, the economic benefit of IWW (USD/m^3) has been improved in 2010. Although economic value is enhanced in all years, improvement in 2010 is substantial compared to other years. Economic value is increased in countries that have a high share of hydropower, mainly in Africa and South America. In this study, we did not consider water withdrawal for hydropower. Dams are constructed for multiple porpuses, but evaporation in the dam reservoir can be counted as a hydropower consumption (M. M. Mekonnen & Hoekstra, 2012).

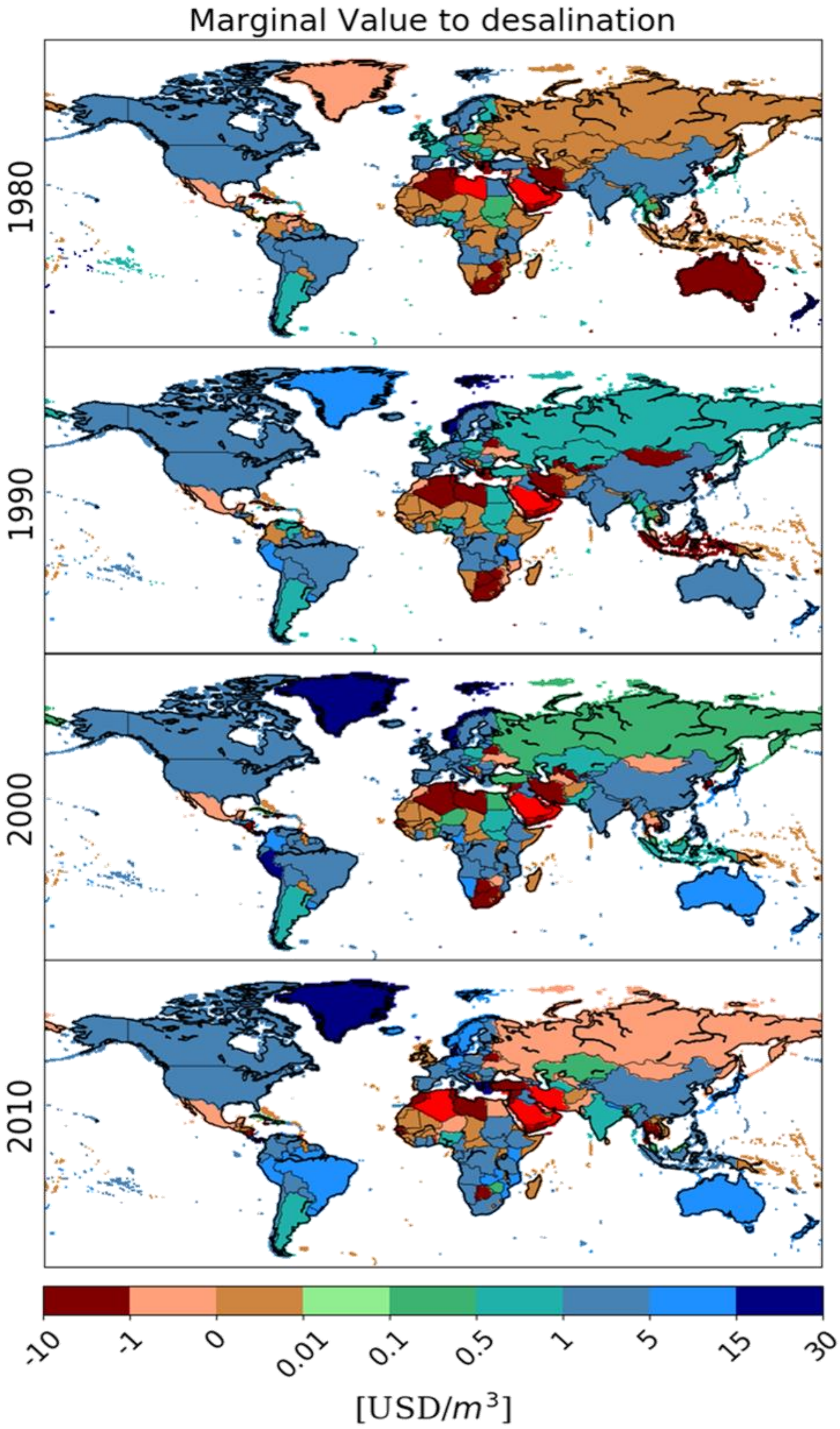


Fig 3.23. The economic value of IWW (USD/m3) by considering hydropower and renewable energy.

3.5 CONCLUSION

This study tried to estimate industrial water withdrawal on a global scale from 1980 to 2010 as a past to the current situation. H08 model could determine the amount of IWW in good condition based on the Willmott index agreement. The result of this study shows that IWW (km^3/year) increases 1.5 times, and it reaches almost 913 km^3 in 2010 compared to nearly 610 km^3 in 1980, although industrial water intensity (m^3/MWh/year) decreases, and it halved during the same time. As expected, industrialized countries withdraw more water than developing countries, although in Europe and North America IWW is decreased after 1990 and 2000 respectively as a result of efficiency growth. The expansion of Asia's IWW is substantial for 30 years.

Along with the IWW quantity assessment, the economic value of the industrial sector on a global scale is estimated for the first time. Unique mythology is applied for the calculation of the economic value of IWW. It is calculated based on comparison with desalination technology as the most energy-intense technology of water production. Reverse Osmosis (RO) desalination technology is selected as the most common technology. Results show that the economic value of the unit amount of IWW (USD/m^3) is continuously increasing. A global average of IWW economic value increases 1.6 times and from almost 1.1 to 1.7 (USD/m^3) during 30 years. In Asia, water value is increased more than 1.4 times, with the average annual growth rate of 1%, since this value for North America is more than 1.6 times and 1.3%. The total economic value of IWW is calculated over the grid level as potential economic value. The global average total economic value of IWW is continuously growing up, and from almost 660 billion USD in 1980, it reaches 1537 billion USD in 2010, which means the economic benefit is increased almost 2.3 times, with average annual growth of 4.4%. In general, economic value is higher in developed countries like Europe or Japan.

This study results demonstrate that water use efficiency and productivity in the industry sector increases over time since both the total and unit amount of IWW economic value increases. Since this study didn't consider the manufacturing industry, therefore the result is underestimated, mostly in industrialized countries like the United States and China that the economic value of IWW is lower compared to other developed nations. Consideration of geological location of power plants and also manufacturing part can increase accuracy and also the importance of economic assessment in the industrial section.

Finally, we assessed hydropower and renewable energy impact on the economic value of IWW. Our result indicated that Hydropower increased 13% of the economic value of IWW (USD/m^3) during the 30 years since renewable energy just grew 1% in the same period. Also, the total economic value increased in all years by considering hydropower and renewable energy. In 2010, the overall global economic benefits increased by 24% and reached nearly 1900 billion USD.

Chapter 4: Domestic

Abstract:

Nowadays, many countries are finding that supply-side solutions alone are not enough to overcome to meet ever-increasing demand. Considering the economic value of water is essential for water planners and managers. This study focuses on the domestic sector for both quantity and economic benefit. We estimate domestic water withdrawal and its economic value on the global scale over the grid-level from 1980 to 2010. Consumer surplus as the economic value of domestic water is calculated on the grid cell scale with building demand function for each grid within a country based on water price in different levels of domestic water intensity. Global domestic water withdrawal increases 2.3 times in 2010 compared to 1980 with the average annual growth rate of 1.9%, from 201 km^3 to 469 km^3, since the population increases 1.5 times during the same period. In 2010 still, almost 660 million people, which 69% from African countries suffer from access to basic water requirements. The global average of the economic value of domestic water is almost 5400 \$/cap in 2010 and increases 3% from 1980, while the total economic amount rises 58% from 1980 and reaches nearly 28 trillion USD in 2010. The total economic value of water intensity in developed countries is much higher than in developing countries. In the Middle Eastern region, with high pressure on water resources, economic value is lower compared to other developed countries with the same level of domestic water withdrawal due to the low level of water price. Along with technological improvement, economic policy transformation is essential, especially in developing countries and water-scarce regions.

Keywords: Value of water, Domestic water withdrawal, Consumer surplus, Water price

4.1 INTRODUCTION

Water scarcity is a critical global issue. Because of increasing demand during the last few decades, freshwater scarcity is one of the vital dilemmas for sustainable development and human society and life (UNDP, 2006).

According to the United Nations Development Programme (UNDP) report (UNDP, 2006) Around 1.2 billion people or almost 20% of the world's population are living in areas of physical water scarcity; also 500 million people are approaching the same situation and more than 20% or 1.6 billion people of the world's population has been threatening by economic water shortage. While considering seasonal and interannual variation, four billion already face extreme water scarcity; It is almost half the world's population (Mesfin M Mekonnen & Hoekstra, 2016). Water demand grows continuously along with population and economic development (Wada et al., 2016) and global water withdrawal increased from 500 km^3/year to 4000 km^3/year from 1900-2010 (Falkenmark, 1997; Shiklomanov, 2000; Vörösmarty, 2005; Wada, 2013).

On the earth, only 0.007% of water is easily accessible freshwater, and it is enough of all human beings, but because of uneven geographical distribution there are water scarcity problems (Oki and Kanae, 2006), for example, the Mediterranean region is home of 7.3% population but only includes 3% of global water resources (Margat & Treyer, 2004).

Since in some regions (e.g., arid and semi-arid regions) total water demand is close to exceed entire renewable freshwater resource, so efficient and integrated water resource management is essential for each drop of water use in these regions (Famiglietti et al., 2011; Wada, van Beek, & Bierkens, 2012; Wada, van Beek, Sperna Weiland, et al., 2012). In regions with high limitation of available water, risk of food production, and economic development likely increase (Wada et al., 2016).

Accessing to enough water (water security) was first addressed as a policy challenge at the World Water Forum in 2000 in the United Nations Ministerial Declaration of The Hague on Water Security in the Twenty-first Century, and still, it is on the agenda of international organizations (Jensen & Wu, 2018; UN-Water, 2013).

Water plays an essential role in our economic and social activities. World Economic Forum continuously pointed water scarcity as a critical risk for businesses that have a high impact on economies, environments, and human life (Jensen & Wu, 2018; World Economic Forum, 2015). In the most developed countries, by building high-cost infrastructure in the supply-side, they overcome this uncertainty to meet sufficient supply and reduce risks, although it has sometimes negative impacts on the environment and human life. But nowadays, many countries are finding that supply-side solutions alone are not enough to overcome to meet ever-increasing demand, so other solutions like demand management are being addressed to overcome insufficient available water (UN-Water, 2008; UN-Water & GWP, 2007). More than half of the world population (3.9 billion people) lived in cities in 2014 (UN DESA, 2014), and it is expected to increase from 54% in 2014 to 66% of the global population by 2050 (Srinivasan et al., 2013), so increasing number of people in urban area can accelerate and intensify water scarcity (Mesfin M Mekonnen & Hoekstra, 2016)

Irrigation is almost 70% of global water use, Industrial and domestic is 18 and 12%, respectively (FAO, 2016a). Although irrigation is the largest and domestic is the smallest water use sector, but some studies estimated a significant change of share of global water withdrawal in the future (Hejazi et al., 2013). WaterGAP2 (Alcamo et al., 2007) projected 41%, 28%, and 31% of global water withdrawal for the agricultural, industrial and domestic sector by 2075 respectively, while Shen et al. (2008) estimated them as 52%, 37%, and 11%. Although domestic water is vital for human-like others, unlike agriculture and industrial demand, it cannot meet by virtual water trade (Neverre & Dumas, 2015).

A limited number of global models are available for domestic water (Wada et al., 2016). Some studies projected Domestic water withdrawal as a function of economic development (GDP) (Alcamo et al., 2003; Flörke et al., 2013; Shen et al., 2008). WaterGAP was the first global hydrological model to project domestic water demand by an empirical sub-model using socio-economic data, population, and GDP per capita (Alcamo et al., 2003). The WaterGAP model incorporates structural and technological change concepts. Structural change means that domestic water intensity (water use per capita) will increase rapidly with income (GDP) increase, but the growth rate will decrease gradually and finally saturate. Technological change defines improvement of water use efficiency by technological development during the time. The relationship between income and consumption is debatable (Hanasaki et al., 2013a); therefore, Hanasaki et al. (2013) proposed a different regression model as a function of time for 21 representative countries of each global region. Other studies try to consider other factors: e.g., water price addition to socio-economic parameter (Hejazi et al., 2013), urbanization rate (P. J. Ward et al., 2010), climate variables and GDP (Hughes et al., 2010) and climate condition, urban and rural population accessibility rate(Wada, Van Beek, & Bierkens, 2011).

The historical record of the domestic water sector is quite poor (Flörke et al., 2013). There are only a few studies about water resource assessment and water use at the global level for the 20th century (Flörke et al., 2013). Food Agriculture Organization (FAO) of the United Nations established comprehensive coverage of water-related datasets in different sectors. It includes domestic water withdrawal historical data at the global level, but still, it is not complete. Sufficient information is essential for understanding water use situations (Showstack, 2011). Water policymakers need adequate data to make the right decision, and it becomes more critical while water resource is scarce.

Economics and engineering complement each other, and they often exchange fundamental ideas (Lund et al., 2006). Along with assessing water amounts, it is additionally essential to have a thought of the economic value related to water uses and the potential financial losses described with water deficiency (Neverre & Dumas, 2015). For example, water pricing is one of the instruments for controlling water demand and recovering the cost, and it has a high potential to increase economic efficiency in case of proper management (Rogers et al., 2002; F. A. Ward & Pulido-Velazquez, 2009). In a developed water system, the cost of the new supply system is high, also with increasing competition among water users from different sectors more comprehensive view is essential to solving conflicts (Harou et al., 2009). Economic valuation can help managers to allocate water in the best way when water is scarce (Harou et al., 2009). In hydro-economic models, water allocates among the users based on the economic value that they can make (Harou et al., 2009). From an economic view, water demands aren’t just numbers; they are functions that have different economic values based on different quantities and types of use (Lund et al., 2006).

Although recently, economic ideas have been applied widely in infrastructure management and system design (Lund et al., 2006), economic valuation is mostly absent from water resource assessments. In large scale assessment, only one study carried out for the Mediterranean region (Neverre & Dumas, 2015), and there is no global assessment. Since there is no market in the water sector, it is hard to estimate the economic value of water, but it is necessary to find out another way for estimation of the economic value of water (Young, 2005a). In domestic water, economic value assessment is carried out by defining demand function, with a willingness to pay for different quantity of water (Young, 2005a).

This study focuses on the demand side of water use and its economic analysis in the domestic sector. Since spatially averaged (e.g., country-wise) water use intensity can lead to some unrealistic estimation (Gleick, 1996), this study tried to calculate water withdrawal over grid cells for 166 countries separately for 1980-2010 time period, applying same approach as a WaterGAP (Alcamo et al., 2003) with revised calculation method. Finally, the economic value of domestic water is calculated in the same spatial and temporal resolution with building demand function using willingness to pay and domestic water use intensity.

4.2 METHODOLOGY

4.2.1 Datasets

Domestic water withdrawal Data

Country scale annual domestic water withdrawal data are obtained from the AQUOSTA dataset of the FAO (FAO, 2016a). AQUASTAT is the most global coverage and reliable source of water statistics dataset (Hejazi et al., 2013). It is a country scale, and data are collected for all available countries. Based on the FAO definition, Domestic (municipal) water withdrawal is the amount of water withdrawn by a public distribution network system and connected to the municipal network. It can be renewable resources, e.g., surface water or groundwater, fossil groundwater or treated wastewater, and it can be used for daily life, e.g., drinking and cleaning, the industry which is connected to the public network, urban landscaping, and irrigation for the urban area. (FAO, 2016a; Hejazi et al., 2013).

GDP and Population

For socio-economic data, GDP, and population, the center of global environmental research (CGER) data (Murakami & Yamagata, 2016) has been applied. The data are estimated by downscaling actual populations and GDPs by country from IMF (international monetary fund) in 0.5 × 0.5-degree grids from 1980 - 2010. They considered auxiliaries variables, e.g., City population, Urban area, agriculture area, the total length of major roads, and distance to ocean and airport. For the population in an urban area, they downscaled from countries to cities and finally to grids level and for the non-urban area directly from countries to grids, since GDP was downscaled from countries to grids level using downscaled populations (Murakami & Yamagata, 2016).

4.2.2 Domestic water use modeling

Annual domestic water withdrawal (hereafter DWW) calculated globally on the grid-scale by following the WaterGAP model and structural change approach (Alcamo *et al.*, 2003a). In structural change (Figure 4.1), water use intensity grows rapidly first and reaches a saturation point with economic growth from low to high and represented by a sigmoid curve. In previous study domestic water withdrawal per capita (DWWC) projected at country scale then distributed to grid-scale based on population distribution (Alcamo *et al.*, 2003a, 2003b; Flörke *et al.*, 2013), but this study calculated DWW for each single grid cell separately using modified WaterGAP model from 1980 to 2010 (Eq. 4.1):

$$DWW = dww_{min} + dww_{maxadd}\left(1 - e^{-\delta GDP^2}\right) \qquad 4.1$$

$$\text{Where, } \mathrm{dww_{maxadd}} = \mathrm{DWW_{sat}} - \mathrm{dww_{min}} \qquad 4.2$$

Where DWW (m^3/year) is domestic water withdrawal, and dww_{min}(m^3/year) is the minimum domestic water withdrawal, $dww_{\boldsymbol{maxadd}}$($m^3$/year) the maximum additional domestic water withdrawal, δ is the curve parameter and $DWW_{\boldsymbol{sat}}$ is domestic water withdrawal at the saturated point, respectively (Alcamo et al., 2003; Neverre & Dumas, 2015). In this method, historical DWW for each grid cell is obtained by multiplying the gridded population to domestic water intensity within the country; then Instead of calibrating the model to per capita domestic water use, it is calibrated on DWW (m^3/year) using gridded GDP data. All of the model parameters are calibrated for each single grid cell. Finally, DWW is calculated and completed for missing year data for all countries from 1980 to 2010 by applying the model (Eq. 4.1) on the grid-scale. In China, since the historical DWW trend is shown huge drop around the year 1995, therfore average DWW value of 1985, 1990 and 1995 is used for the year 1990 DWW and model is fitted by using 1980, 1990, 2000, 2005 and 2010 data.

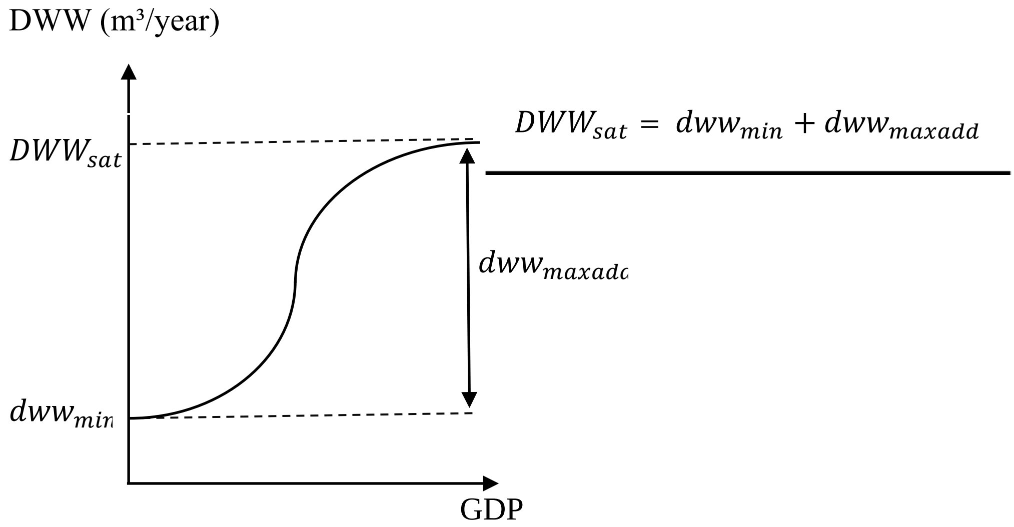


Fig 4.1. Structural change of DWW and GDP, with dww_{min}, dww_{maxadd} and DWW_{sat}.

Water use related to the amount of water that people use for some purpose and consists of water withdrawal, consumption, and return flows. In definition, the amount of water that is obtained from different water sources, e.g., surface water or groundwater to meet demand, is water withdrawal (Flörke et al., 2013; Shaffer & Runkle, 2007). The domestic water use in this study means the domestic water withdrawal, since some part of water withdrawal returns into the water cycle, it can't refer to the water losses (Voß et al., 2009).

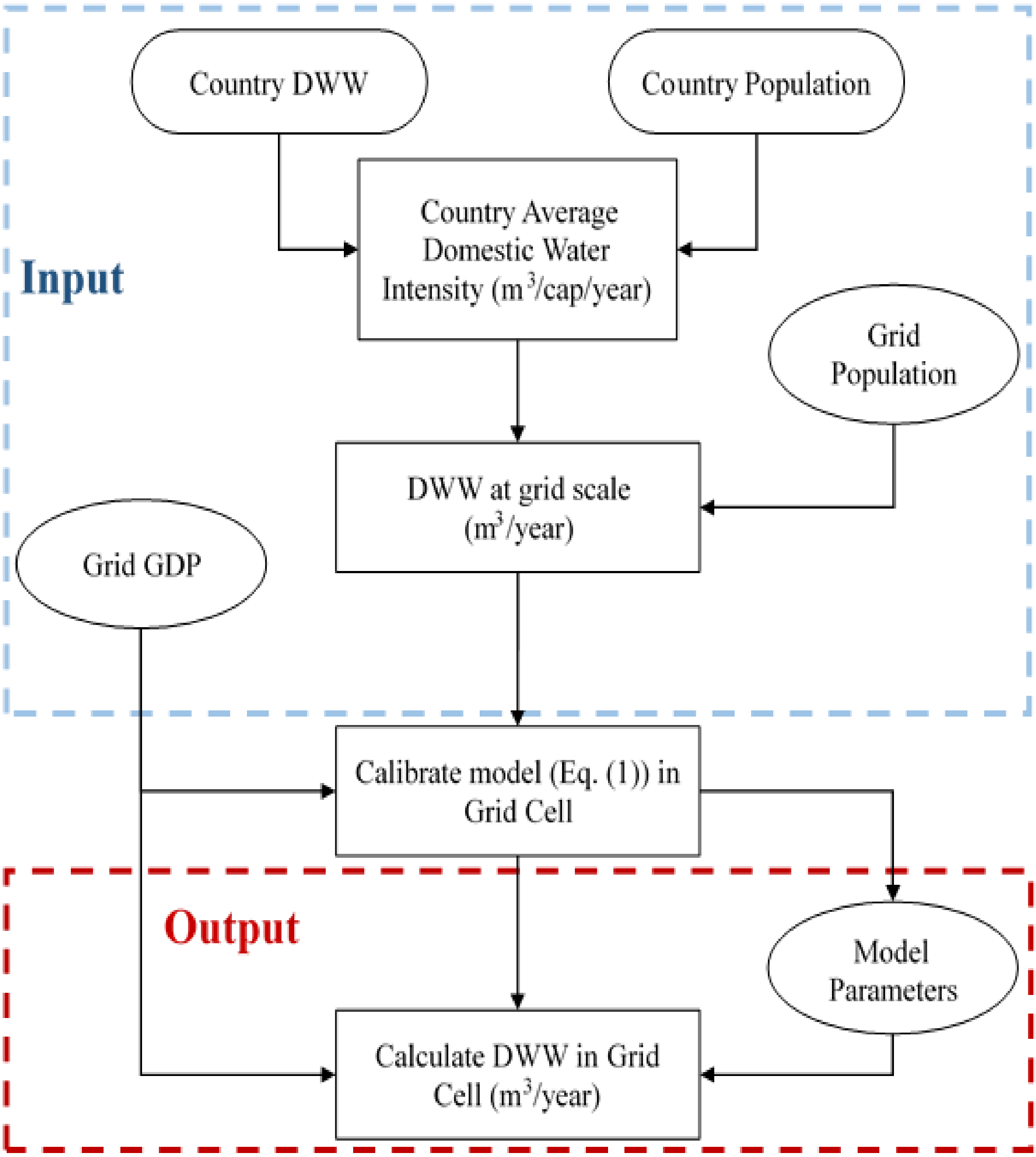


Fig 4.2. Domestic water withdrawal calculation method. Country DWW data is obtained from AQUASTAT (FAO, 2016a), the Country population is from United Nation (UN DESA, 2017) and grid population and GDP is from CGER (Murakami & Yamagata, 2016).

For model performance evaluation, Willmott index of agreement (Willmott et al., 2012) is calculated at the same spatial level (Eq. 4.3):

$$d = 1 \frac{\sum_{i=1}^{n} |Pi - Oi|}{\sum_{i=1}^{n} \left(|Pi - \overline{O}| + |Oi - \overline{O}| \right)} \qquad 4.3$$

Where:

$\boldsymbol{d}$ is Index of agreement, Pi is model-simulation values, Oi is observation values, and $\overline{O}$ is observation mean. $\boldsymbol{d}$ value changes between 0 and 1. One point as total agreement and 0 indicates a complete disagreement.

4.2.3 Demand function and Willingness to pay

Water value differs for different quantities and uses (Harou et al. 2009). Following Neverre et al. (Neverre & Dumas 2015), three-part demand functions are built at first for country scale and then distributed to grid cells within the country in which each part represents the different types of domestic water use (figure. 4.3). The first part is an essential demand, e.g., preparing food or hygiene, and the last part is the least essential demand, e.g., pool or washing mashie (Neverre & Dumas, 2015). With increasing quantity, marginal willingness to pay (WTP) will decrease (Harou et al., 2009). For building demand function, the upper bound of each demand (DW) and related willingness to pay is determined. For the first two-part demand amount (DW) fixed amount is applied (Table 1). Based on the previous study (Gleick, 1996), 18.25 m³/capita/year (50 l/capita/d) is a basic human need, so it is fixed For DW_1.

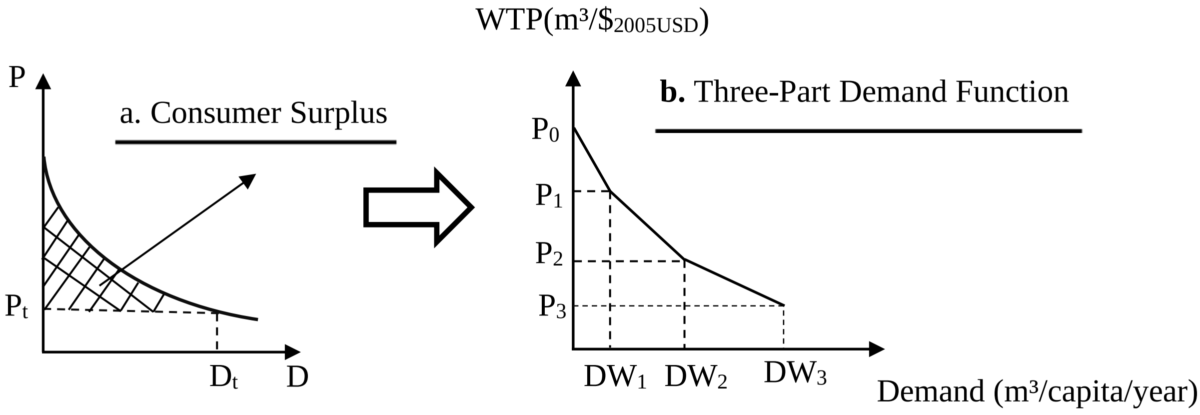


Fig 4.3. **a.** The general structure of the demand function **b.** three-part demand function.

Table 4-1 Different levels of domestic water demand with the definition are obtained from the literature.

Reference	Definition	Water amount
Gleick (1996)	Basic water need	18.25 m^3/capita/year (50 l/capita/d)
Howard and Bartram (2003)	Optimal access with a very low level of health concern	36.5 m^3/capita/year (100 l/capita/d)

For the upper bound of the second block (DW_2), 36.5 25 m^3/capita/year is fixed based on the literature (Howard & Bartram, 2003) (Table 4.1).

Based on model calibration for each grid cell, DWW at saturated point (DWW_{sat}), as the maximum value of DWW, is calculated on the grid-scale (figure 4.1 and Eq. 4.2). With summing all maximum DWW_{sat} at the grid level within the country and dividing by palpation, the upper bound of the 3rd block is obtained as a maximum water intensity at the country scale ($DWWC_{sat-country}$). In some grid cells (6% of all grid cells), if DWWC in some years is higher than $DWWC_{sat-country}$, then maximum water intensity at country scale is considered as a DWWC at that year. It is noted that minimum demand set to 1 m^3/capita/year.

Now we need to set marginal willingness pay related to each demand amount. MWTP for one m^3/capita/year is considered the average price of pet bottle for each country. Price of pet bottle is obtained based on a market survey for each country.

Neverre et al. (2015) assigned a fixed value of MWTP for DW_1 and DW_2 for all Mediterranean countries with different levels of income and development. They fixed 50 $US\$_{2005}/m^3$ (their assumption) for the first block and 14 $US\$_{2005}/m^3$ (literature review) for the second block, but in this study since MWTP is directly affected by income, countries are divided to 4 income categories (high, upper-middle, lower-middle, and low) based on World Bank income category by using GNI (Gross national income) per capita (The World Bank Group, 2018). Since the income category threshold is available after 1987, so the 1987 year's threshold is applied for years before 1987, and for the countries in which GNI per capita isn't available for some years, the income category is considered as same as the first available year data. After categorizing, the maximum observed water price from available data of each group is defined as an MWTP for DW_1 and DW_2 (table 4.2). Only for upper-middle-income countries average price of lower-middle-income and high-income countries is used, because the maximum price of upper-middle-income countries is smaller than lower-middle-income countries. For the MWTP of DW_3, available data on water prices for each country is used (table 4.3). Table 4.2 summarizes of DW and its MWTP for different categories.

Table 4-2 DW and its MWTP for different categories. MWTP data from the International Benchmarking Network of the World Bank (IBNET, 2017) is used.

Refrence	Amount [m³/capita/year]	MWTP [$US\$_{2005}/m^3$]
1	1	The average price of bottled water
DW1	18.25	Maximum price of each category(IBNET)
DW2	36.5	Maximum price of each category(IBNET)
DW3	Calculated for each country	water price of each country (IBNET)

Table 4-3 Country category and MWTP for DW1 and DW2.

World Bank Category	DW_1 MWTP [US$2005/m³]	DW_2 MWTP [US$2005/m³]
Low income	5	2
Lower middle income	12	5
Upper middle income	17	8
High income	22	10

After defining demand and its associated MWTP for three categories, the linear demand function has been applied for each country then distributed to grid cells within the country. MWTP for the specified amount of DWWC can be calculated with linear interpolation through demand function of each grid and with calculating consumer surplus for each grid cells for a different year, the economic value of water for domestic water is calculated for each year from 1980 to 2010 over grid level (Neverre & Dumas, 2015).

4.3 RESULT

4.3.1 Global distribution of domestic water demand

DWW is calculated for 166 individual countries over a half degree. With available data, the sigmoid curve (Eq. 4.1) is fitted and calibrated for each single grid cell for the whole globe.

The Model calibrated to each grid globally at the first step for available data. In this step the minimum water withdrawal ($\boldsymbol{dww_{min}}$ (m^3/year)), the maximum additional water withdrawal ($\boldsymbol{dww_{maxadd}}$ (m^3/year)), and the curve parameter (δ) is obtained after calibration for each grid cell. Then, missing domestic water withdrawal (DWW) is calculated based on each grid specific GDP from 1980 to 2010.

In most of the grids, the Willmott index is more significant than 0.5, and the model fitted successfully. In a country with more available historical data, e.g., China, India, and the USA model fitted well. In most European countries, although the number of available data was sufficient since the model couldn't trace fluctuation in the saturation area, the fitting result is lower than countries with the same amount of available data (figure 4.4).

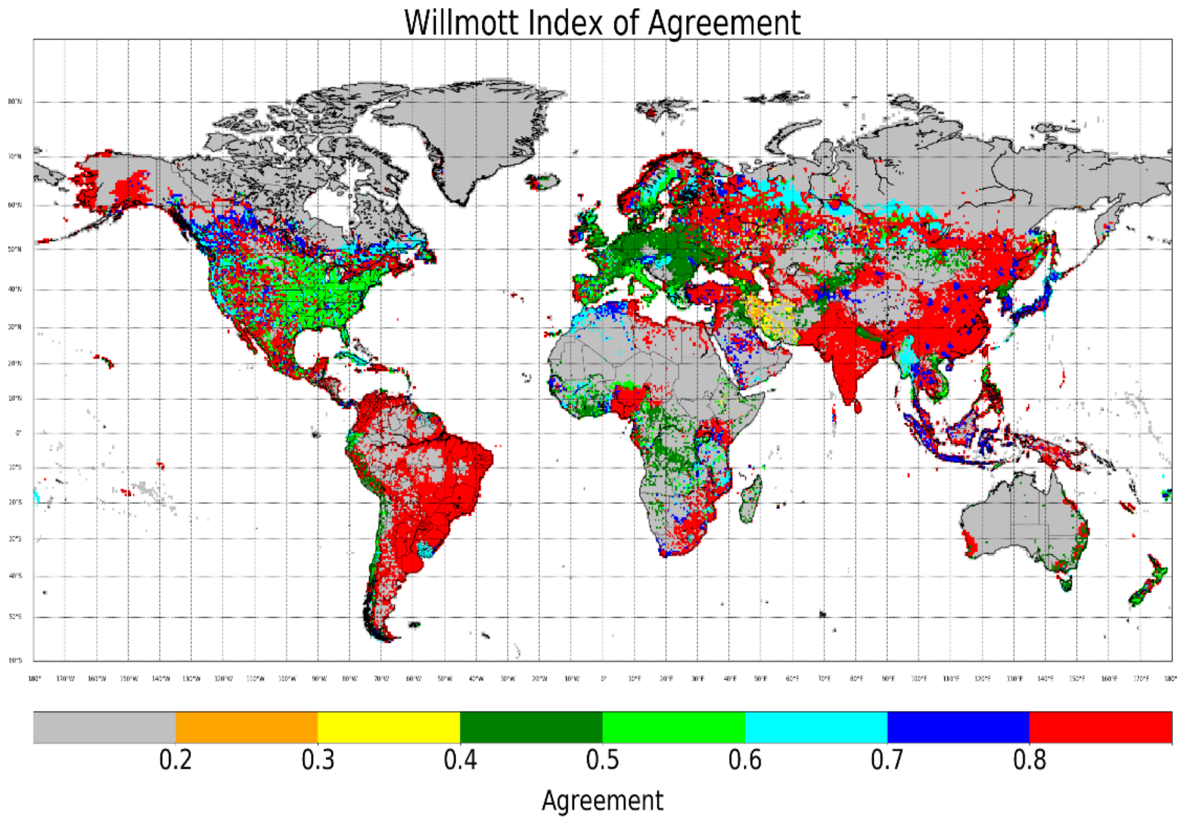


Fig 4.4. Evaluated goodness of fit over grid cells.

Figure 4.5 and 4.6 shows the global spatial distribution of DWW (mm per year) and DWWC (m^3/year/cap). In 1980 in a developed country like the United States, Japan, Western Europe, and population-dense areas like India and China, DWW is high. Also, DWW shows a high amount in coastal line areas and big cities. In 1990 DWW in West African countries, DWW decreases compare to 1980 while in Egypt along with Nile River shows a substantial increase. From 1990 to 2000 shows significant, especially in China and India, due to both population and economic wealth growth, and DWW continued to grow in 2010. The increase in DWW around the Nile River from 1980 to 2010 is significant compared to other global big rivers. Despite water scarcity in the Middle East, DWW is substantial, especially in the urban area.

Taking national average water use data can cause underestimation of the accounting number of people that can't access to basic water requirement (Gleick, 1996), so grid-scale analysis can unhide small scale, e.g., city, regional and basin variation (figure 4.4 and 4.5). The number of people who can't access basic water needs is decreasing from 1.61 billion to 660 million from 1980 to 2010 in the world. As the ratio is 1980, 16% from African and 80% are from Asian countries, but in 2010 it changes to 69% from African 25% from Asian countries (Table 4.4).

Table 4-4 Number of people below 18.25m^3/year/cap in a million.

Continent	1980	1985	1990	1995	2000	2005	2010
Africa	252	313	418	408	390	415	455
Asia	1293	939	957	268	311	188	168
Europe	28	16	15	13	14	13	14
North America	24	21	24	11	9	10	9
Oceania	4	5	5	2	1	2	2
South America	11	5	8	8	9	10	11
Global	1612	1299	1427	710	733	638	659

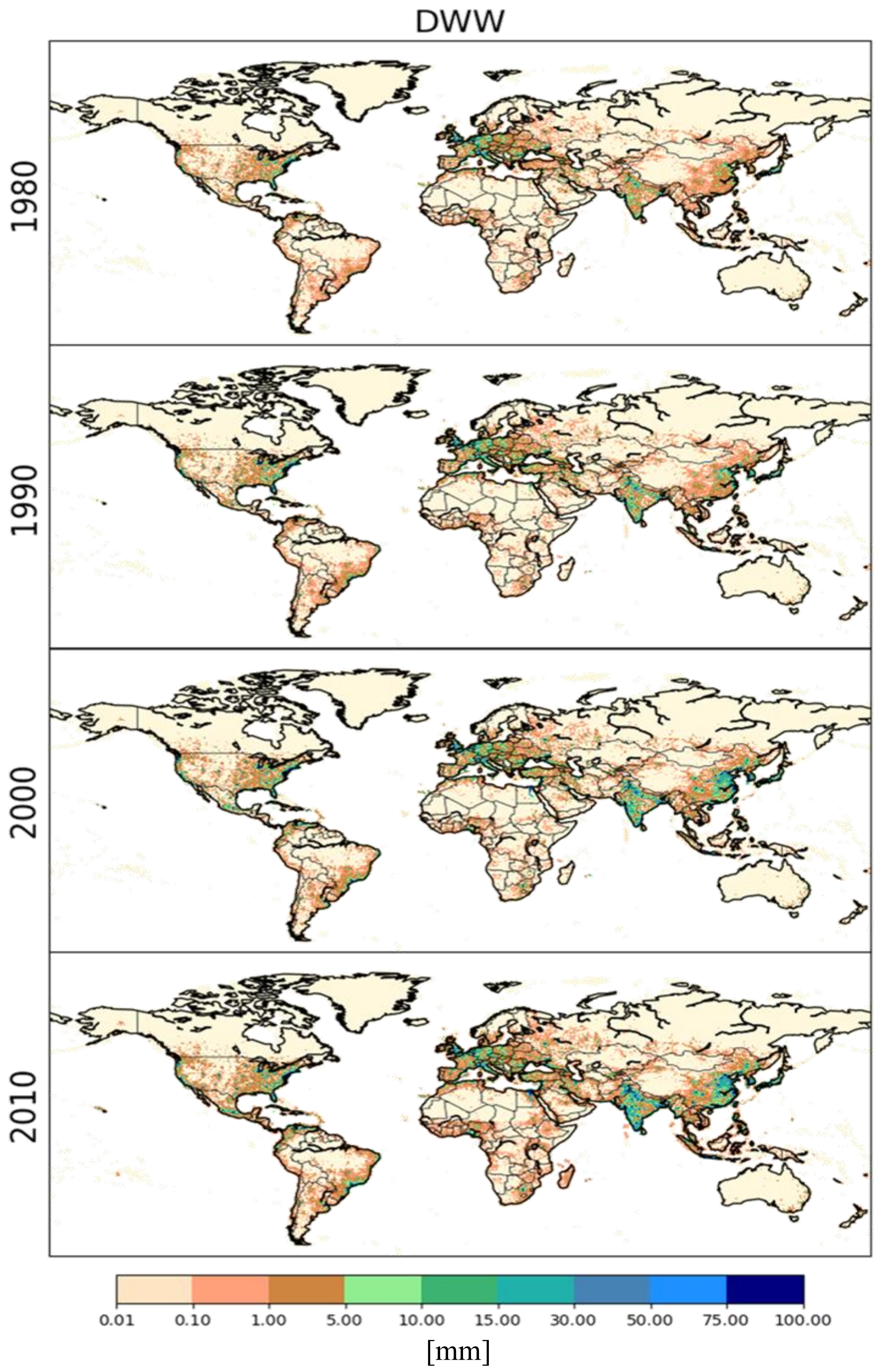


Fig 4.5. Global distribution of domestic water withdrawal (DWW) [mm] at the grid level from 1980 to 2010. Just grid cells with more than 5000 inhabitants are considered from 1980 to 2010 over grid cells.

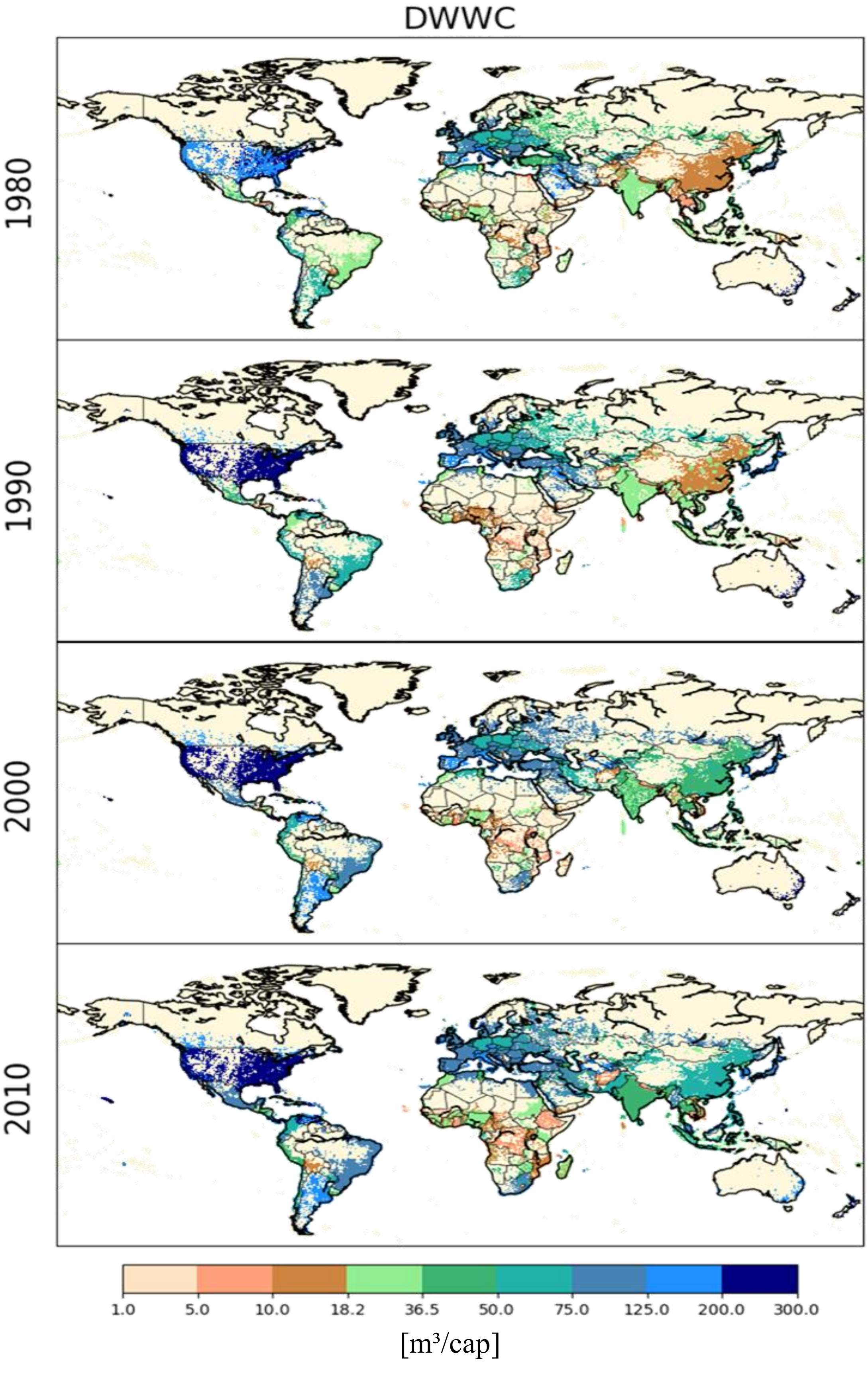


Fig 4.6. Global distribution of domestic water withdrawal per capita (DWWC) [m^3/cap] on grid level from 1980 to 2010. Just grid cells with more than 5000 inhabitants are considered from 1980 to 2010 over grid cells.

Global DWW is increased 2.3 times in 2010 compared to 1980; it means the average annual growth rate is 1.9%. In continental-scale DWW is increased 3, 3.3, 1.3, 1.9, 1.3, and 3.3 times with a yearly average increase of 2.2, 2.3, 0.8, 1.6, 0.7 and 2.3% for Africa, Asia Europe, North America, Oceania, and South America respectively (figure 4.7). The global population increases 1.5 times and 2.1, 1.6, 1, 1.4, 1.6, and 1.6 in Africa, Asia Europe, North America, Oceania, and South America continent, respectively (table 4.5). It is noticed that in all continents except Oceania, the population growth rate is lower than the DWW growth rate. For Oceania region, it can refer to proper water management to increase domestic water use efficiency, mostly in the water-scarce areas. In the continents with more number of developed countries, (e.g., Europe, North America, and Oceania) DWW growth rate is lower than continents which home of developing or least developed countries and growth rate of DWW for these continents are almost same (for Europe and Oceania is bellow than 1%). Indeed in these countries, DWW reaches saturation demand (plateau in the sigmoid curve) (Neverre & Dumas, 2015). Asia and South America have the highest growth rate of DWW, although DWW is increased three times during 30 years in Africa, in terms of water use intensity are the lowest (Table 4.6). It may refer to a lack of infrastructure, and a well-equipped city's water network distribution system (Shiklomanov, 2000) hat can restrict access to enough amount of water due to lack of adequate efforts (Gleick, 1996).

Table 4-5. Continental and global population.

Population (billion)	pop1980	pop1985	pop1990	pop1995	pop2000	pop2005	pop2010
Africa	0.48	0.55	0.62	0.71	0.81	0.91	1.02
Asia	2.63	2.90	3.17	3.45	3.72	3.92	4.12
Europe	0.72	0.73	0.74	0.75	0.76	0.76	0.76
North America	0.37	0.40	0.42	0.46	0.49	0.51	0.54
Oceania	0.02	0.02	0.03	0.03	0.03	0.03	0.04
South America	0.24	0.27	0.29	0.32	0.35	0.37	0.39
Global	4.47	4.87	5.28	5.72	6.16	6.51	6.86

The continental population is calculated by summing grid data of each continent based on CGER data.

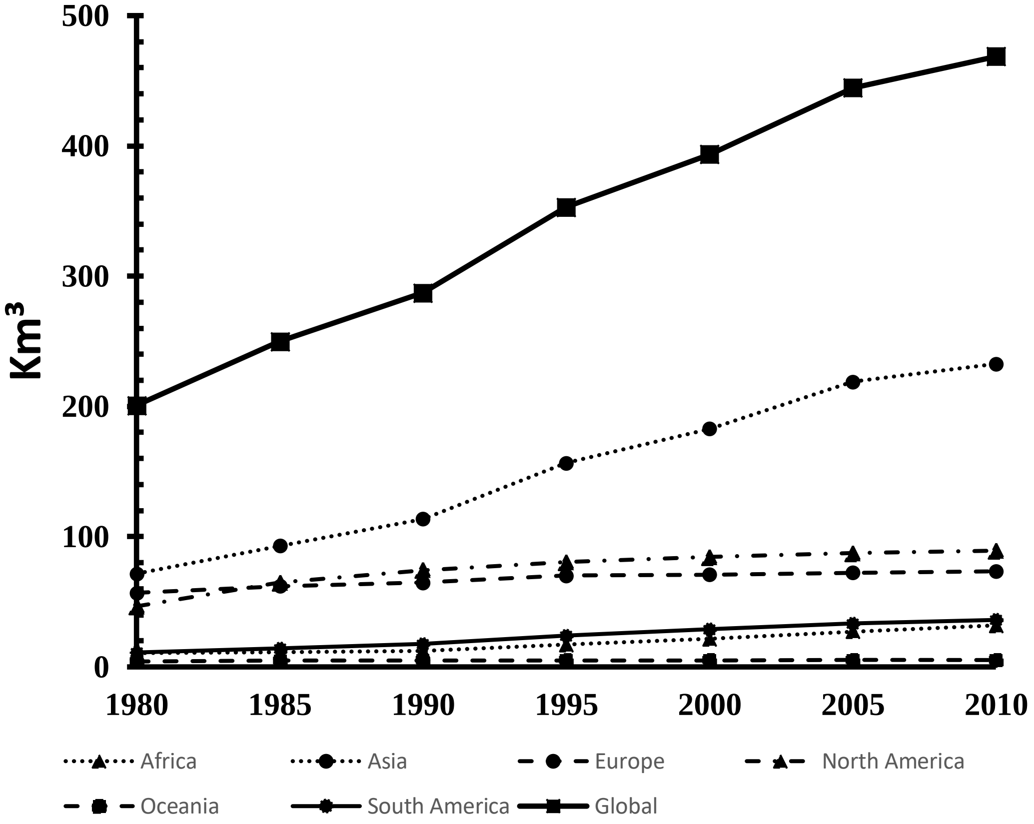


Fig 4.7. Global and continental DWW (km³/year) from 1980 to 2010.

Table 4-6. Global and continental domestic water intensity **(m³/year/cap).**

DWWC (m³/year/cap)	1980	1985	1990	1995	2000	2005	2010
Africa	22.35	20.35	19.38	23.90	26.59	29.71	31.25
Asia	27.22	32.08	35.83	45.39	49.13	55.83	56.42
Europe	78.86	84.80	87.64	93.67	93.42	95.63	97.15
North America	124.08	162.58	176.39	176.34	172.20	170.19	166.25
Oceania	184.41	199.51	189.08	176.75	166.17	157.57	148.10
South America	45.97	52.93	59.33	74.62	83.08	90.05	91.96
Global	44.98	51.31	54.44	61.76	63.94	68.28	68.26

Continental and global water intensity are calculated as of based table 4.5 and figure 4.7.

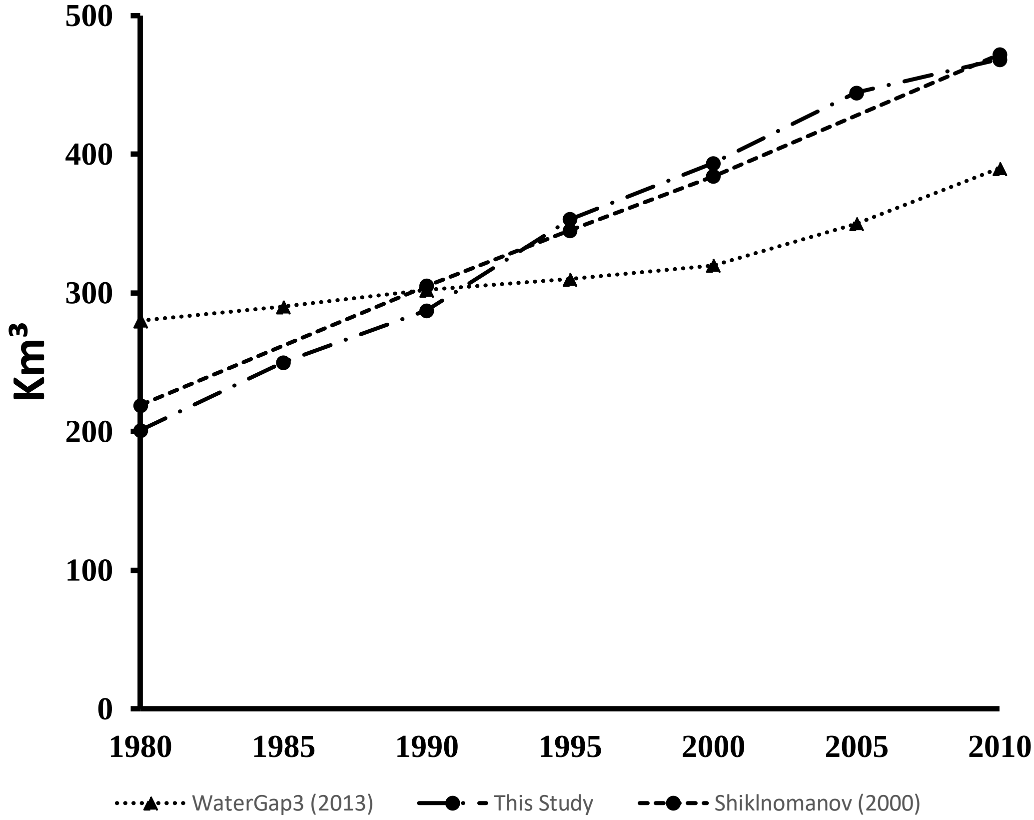


Fig 4.8. Result comparison with past studies. The digitization obtains DWW amount of WaterGap3 (Flörke et al. 2013)

In comparison with other global demotic water studies (Flörke et al., 2013; Shiklomanov, 2000) (figure 4.8), this study results has lower DWW amount from 1980 to 1990 and after 1995 increases with the highest slope (almost 10km³/year) till 2005 and after that the growth rate decreases to almost 5km³/year, while WaterGAP3 (Flörke et al., 2013) accounts for nearly 8m³/year.

2010 DWW is 469km³ for this study and 390km³ and 472km³ for WaterGAP3 and Shiklomanov (Flörke et al., 2013; Shiklomanov, 2000) respectively. From early 1980s water resource management attitude was changed toward increasing efficiency and water pricing policy to control the endless water demand (Arbués & Villanúa, 2006; Gleick, 2000), but after 1995 due to economic wealth and population increase in Asia and African nation (Flörke et al., 2013), DWW increases is significant. Despite WaterGAP3 (Flörke et al., 2013), this study didn't consider a technological improvement since we believed that technological development encompasses available DWW data (available DWW data trend, particularly in a developed country), so accounting technology improvement causes underestimation.

4.3.2 Demand Function and Economic Value of Domestic Water Use

The demand function of each country is calculated by the mentioned methodology (section 4.2.3). Figure 4.9 and 4.10 shows how MWTP is changing for different quantity demanded in continental scale and World Bank income categories. As expected, the highest MWTP for one m^3 belongs to the high-income category, and the lowest MWTP for one m^3 belongs to the low-income group, although MWTP for the lower middle income and low-income category is almost same (figure 4.9). It can be because of the lack of technology and infrastructure in low-income category countries. For others, the high-income category has the highest and low-income group has the lowest in both of MWTP and water demand.

In the continental scale (figure 4.10) Oceania has the highest, and Asia has the lowest MWTP for one m^3 and Africa has the almost same MWTP with Europe, since most of the low-income countries located in Africa continent, this has the same reason which is mentioned about low-income category countries as Africa has the lowest value for other MWTP and water demand. Europe has the highest MWTP for other water demand, but Europe's maximum water demand is just higher than in Africa. European countries have less level of domestic water intensity compare to other countries with the same level of the economic situation, so this can be because of the climate conditions in Europe.

In general, WTP of water in developed countries is higher than developing countries, and the demand curve for the second and third block is flat compared to the first block, it shows the first block water demand in an inelastic and second and third block is elastic. It makes sense while the first block of water demand is essential to demand, and WTP is not changing a lot with the change of quantity. The minimum value of MWTP is a water price that delivers trough pipeline to the household.

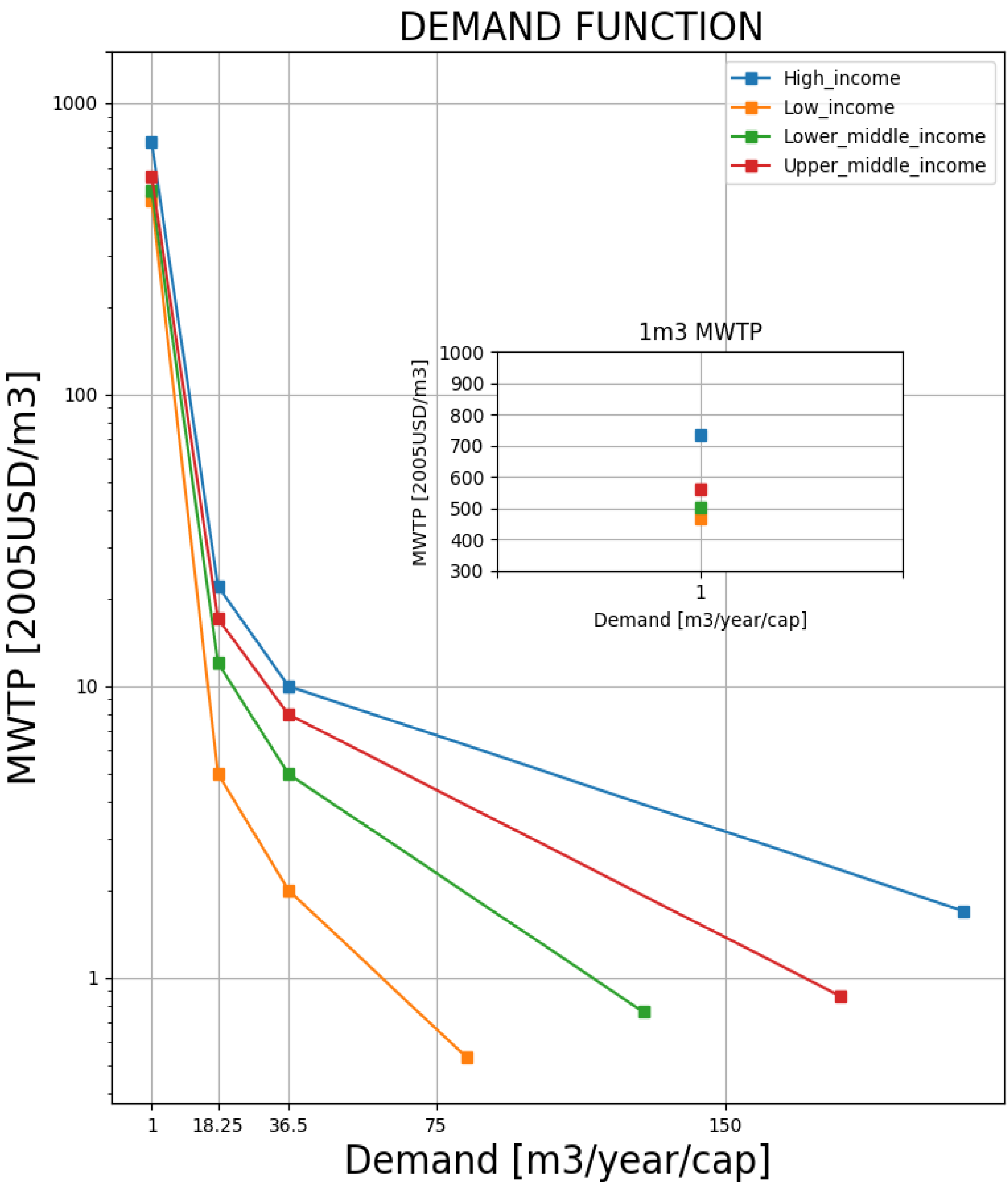


Fig 4.9. Demand function on each continent. (Y-axis is a logarithmic scale).

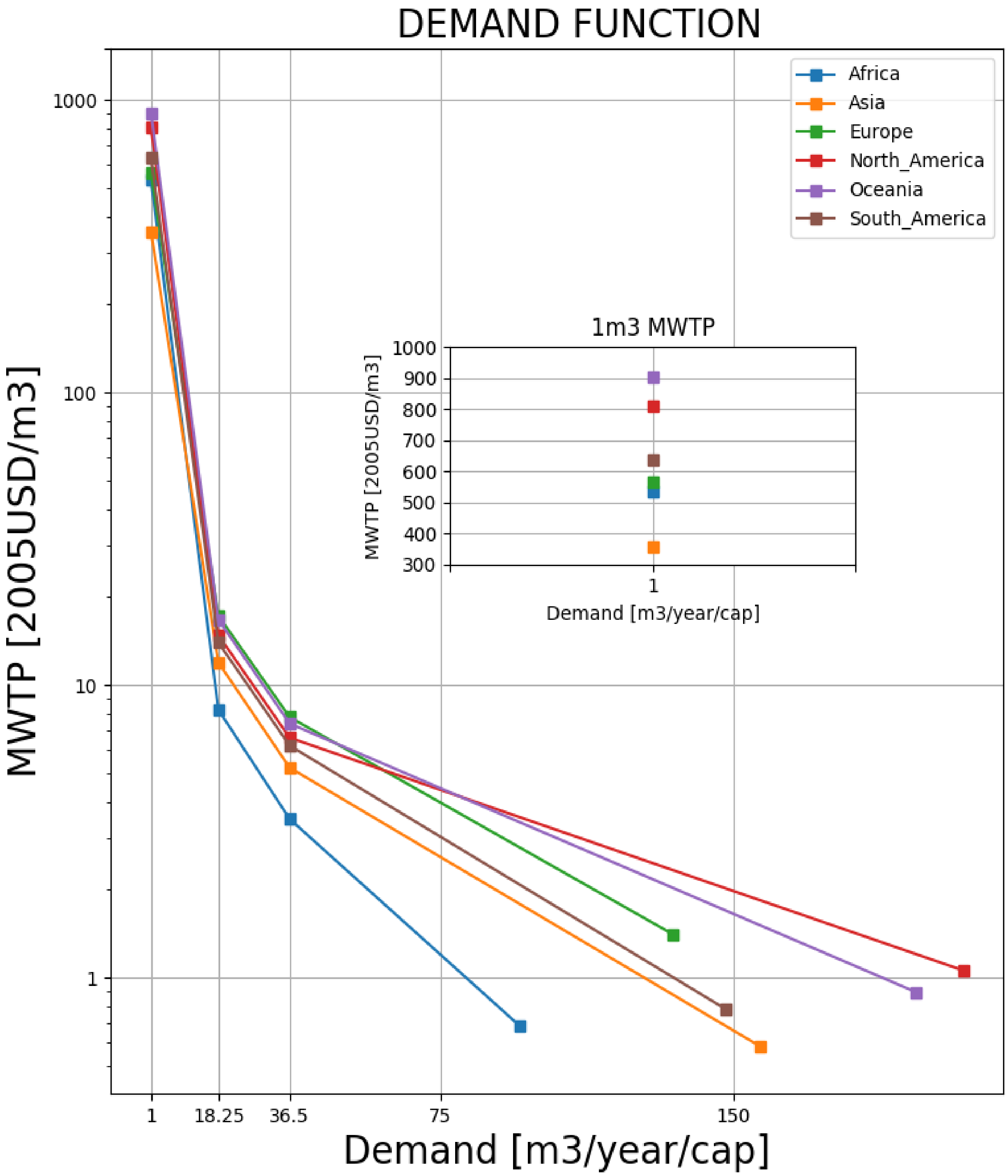


Fig 4.10. The demand function for the World Bank Income category. (Y-axis is a logarithmic scale).

Consumer surplus as representative of the economic value of domestic water withdrawal is calculated on the grid-scale (section 4.2.3). Figure 4.11 shows consumer surplus ($/year/cap) for 30 years from 1980 to 2010 over the grid level. In most of the countries, the surplus is less than 6000 $/cap. The highest value of surplus is captured in Iceland and Norway and also the United States. Countries with over 6000 $/cap surplus value can be divided into three substantial categories. The first is, in some African countries, the surplus is higher than 6000 $/cap because of the high price of water, since their DWWC value is below than developed countries and in some regions also below basic human requirement (18.25 m^3/year/cap (Gleick, 1996)). It seems that these countries lack technology and infrastructure limit people to access enough water at a reasonable price, although these countries are rich in terms of water resources. The second group is the countries like the United States and Australia that have high value in both water pricing and DWWC. In these countries, surplus value is more weighted to DWWC. The last group is the counties which have very high water price with high DWWC, Mostly in European countries. In these countries, although DWWC is lower compared to other countries with the same economic condition, because of the high price of water, its surplus is also high. In the Middle East region by the same level of water use (or higher) with European countries, the economic benefit of water use was smaller than these countries. In the Middle East region, the surplus is bellow than 6000$/cap and in some countries is below 3500 $/cap. It is substantial than in drought region with high pressure on a water resource; the surplus is less while DWWC is high. Country policy for water pricing could be one of the reasons because Australia is an excellent example of taking a good strategy for water pricing and demand during the county with pressure on the water resource. In general, water, the value was higher in developed countries compared to others. Also, in these countries, due to the negative effect of water price after reaching a saturation point, surplus slightly starts to decreasing (Neverre & Dumas, 2015), but in developing countries, surplus is increasing.

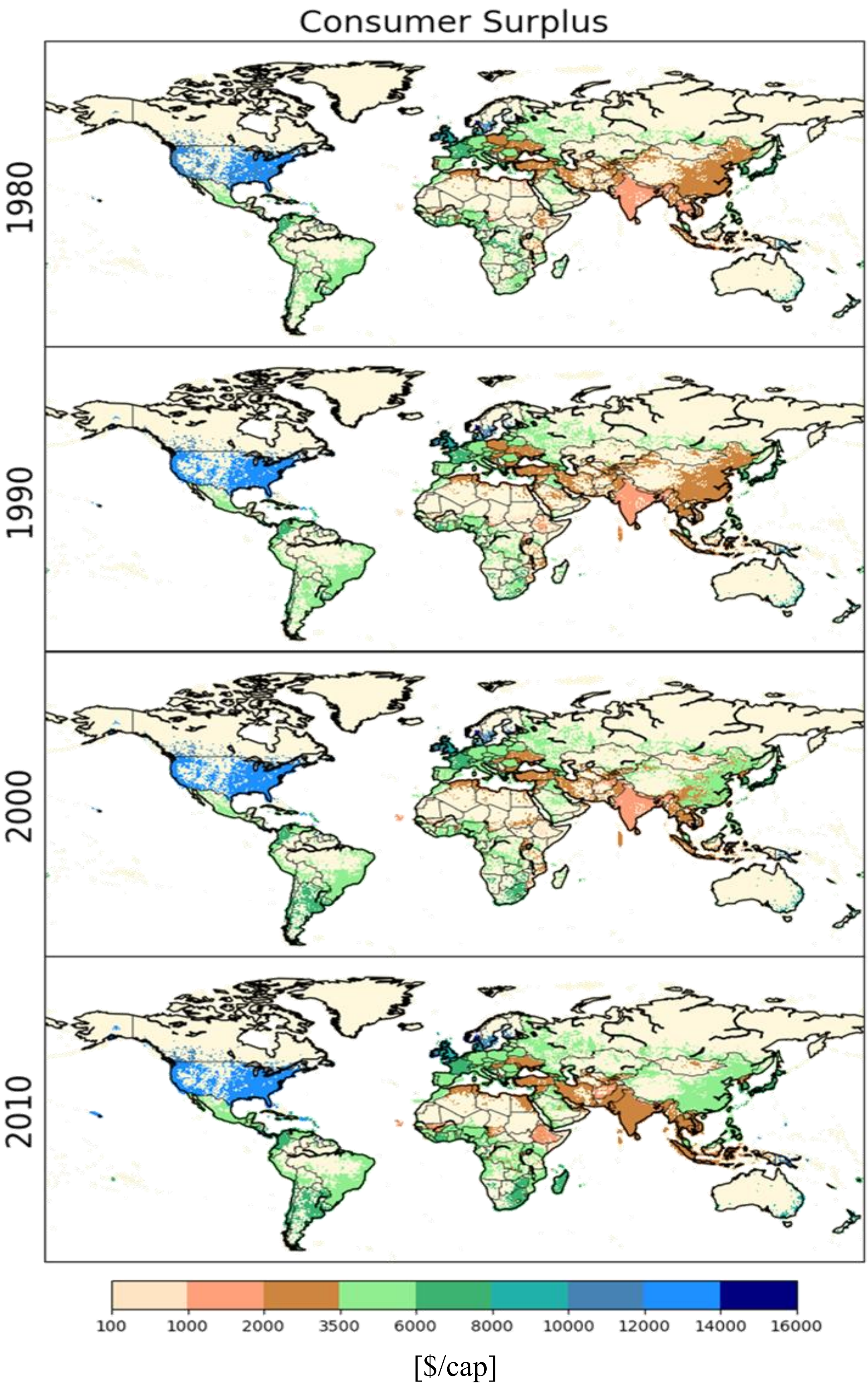
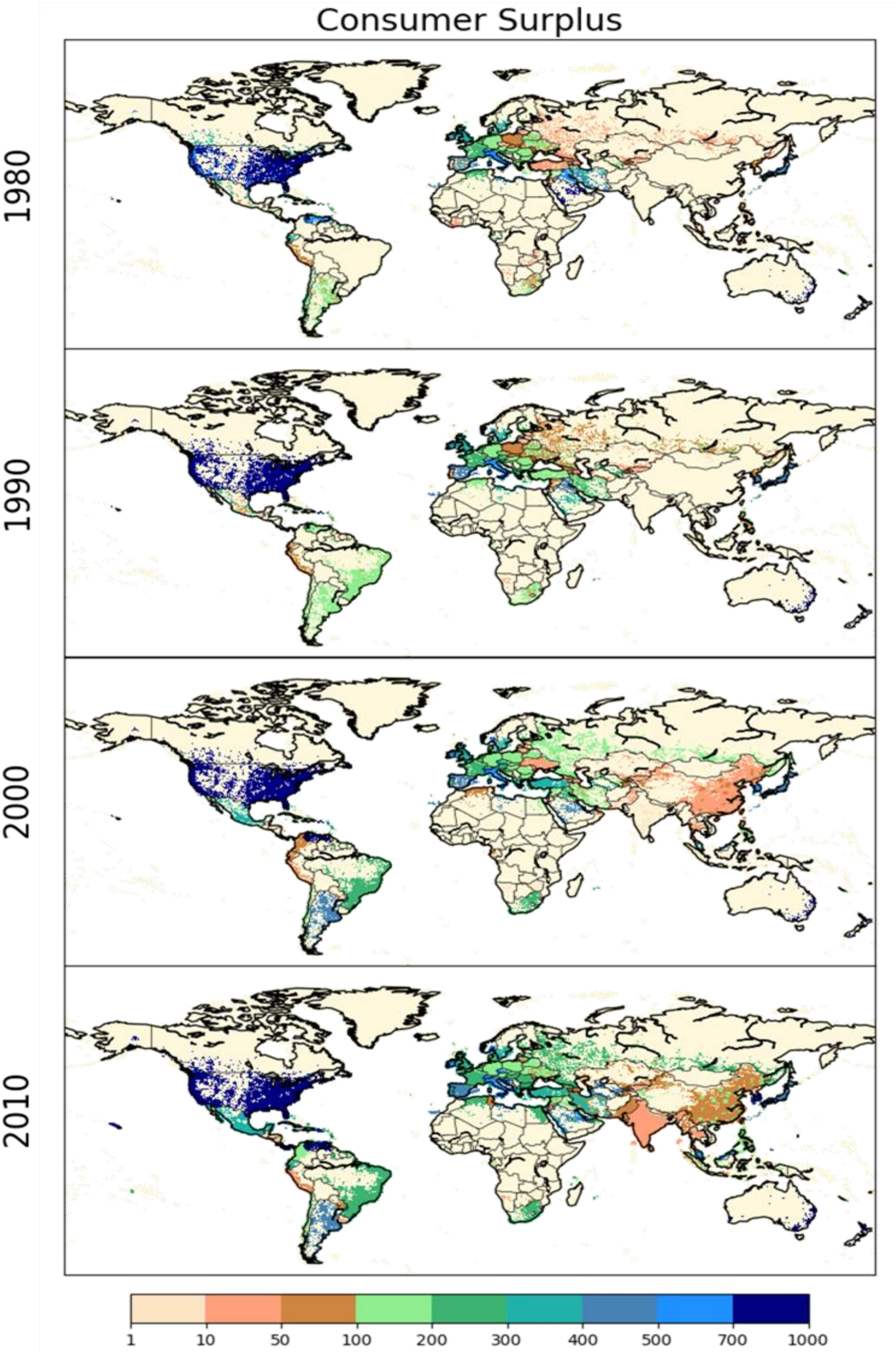


Fig 4.11. Consumer surplus (economic value) for all domestic water intensity over the grid level. Just grid cells with more than 5000 inhabitants are considered from 1980 to 2010 over grid cells.



[$/cap]

Fig 4.12. Consumer surplus for the third block (appear for grids in which domestic water intensity is bigger than 36.5 (m^3/year/cap)). Just grid cells with more than 5000 inhabitants are considered from 1980 to 2010 over grid cells.

Although the consumer surplus of all countries is changing from 1980 to 2010, it is difficult to show, since the changing rate is low. The average global surplus is increased by 3% for 30 years, with an average annual growth rate of 5$/year/cap (0.1%/year) (table 4.7 and 4.8). The surplus growth rate is lower compared to the DWWC growth rate (1.1%/year). On the continental scale, Oceania has the highest, and Asia has the smallest surplus (figure 4.13 a), although Asia has the highest growth rate from 1980 to 2010 (figure 4.14 a). Europe has the highest water pricing (except for 1m^3, (figure 4.10)), But domestic water intensity in Europe (table 4.6) is lower than Oceania and North America, so as a result, the difference in surplus is significant to compare to North America and Oceania. Higher surplus-value in Africa compared to Asia could be the result of high water price in 1 m^3 (figure 4.10), and both Asia and Africa continent surplus-value is below global consumer surplus, especially in Asia with more than 1800$/cap difference (Table 4.7). In Oceania and North America, surplus value is almost two times compare to Asia and Africa.

In general, in most continents, the surplus-value change around 2005 and 2010 is greater than in other years. Before 1995 growth rates of almost all continents are below the global growth rate, and just in Oceania after 1995, the growth rate is below zero. Growth rates have accelerated after 2000 in all continents (figure 4.14 a).

In World Bank Income Category countries (table 4.8 and figure 4.13 b), as expected, high-income countries have the highest surplus and almost two times compared to low-income countries. Low income and lower-middle-income countries are virtually in the same level of surplus value after 1995, and upper-middle-income countries have the highest growth rate from 1980 to 2005, but low-income countries have the highest growth rate from 2005 to 2010. The massive drop in growth rate from 2005 to 2010 is remarkable in high-income and upper-middle-income countries since the growth rate is upward for low income and lower-middle-income countries in the same period (figure 4.14 b).

In 1980 upper-middle-income countries' average surplus-value is a little bit above the global consumer surplus value (Table 4.8), and it is increasing too far above the global consumer surplus value from 1985 to 2005, but after that with huge drop approach to global consumer surplus.

In both low income and lower-middle-income countries, the average surplus is behind the global value (almost 1000$/cap difference in low-income countries), and the difference value stays virtually constant during the time. After 1990 consumer surplus in high-income countries is decreasing, and the growth rate is becoming negative after 1995 (figure 4.14 b). Lower-middle-income countries are the only one that has negative consumer surplus growth rate from 1980 to 2010, although it is upward from 2005 to 2010 (figure 4.14 b).

Table 4-7 Consumer surplus for each continent [$/cap].

Continent	Surplus[$/cap]						
	1980	1985	1990	1995	2000	2005	2010
Africa	4970	4953	4943	4965	4981	5007	5039
Asia	3414	3459	3466	3509	3528	3569	3641
Europe	5654	5665	5681	5695	5725	5785	5851
North America	7999	8092	8059	8057	8146	8193	8230
Oceania	9126	9129	9128	9121	9109	9002	9080
South America	6145	6127	6150	6205	6273	6273	6380
Global	5278	5302	5305	5326	5351	5388	5443

Consumer surplus of this study in continental-scale is calculated as individually, it means instead of taking the average of grids, and then countries of each continent, consumer surplus is calculated directly by demand function of each continent (figure 4.10).

Table 4-8 Consumer surplus for The World Bank income category [$/cap].

Income	Surplus[$/cap]						
	1980	1985	1990	1995	2000	2005	2010
High income	7814	7790	8056	7909	7810	7692	7165
Upper middle income	5421	5678	5637	5734	6080	6086	5511
Lower middle income	5212	5209	5113	4925	4677	4490	4562
Low income	4066	4107	4232	4479	4350	4433	4527
Global	5278	5302	5305	5326	5351	5388	5443

Consumer surplus of this study in The World Bank income category is calculated as individually, it means instead of taking the average of grids, and then countries of each category, consumer surplus is calculated directly by demand function of each category (figure 4.9).

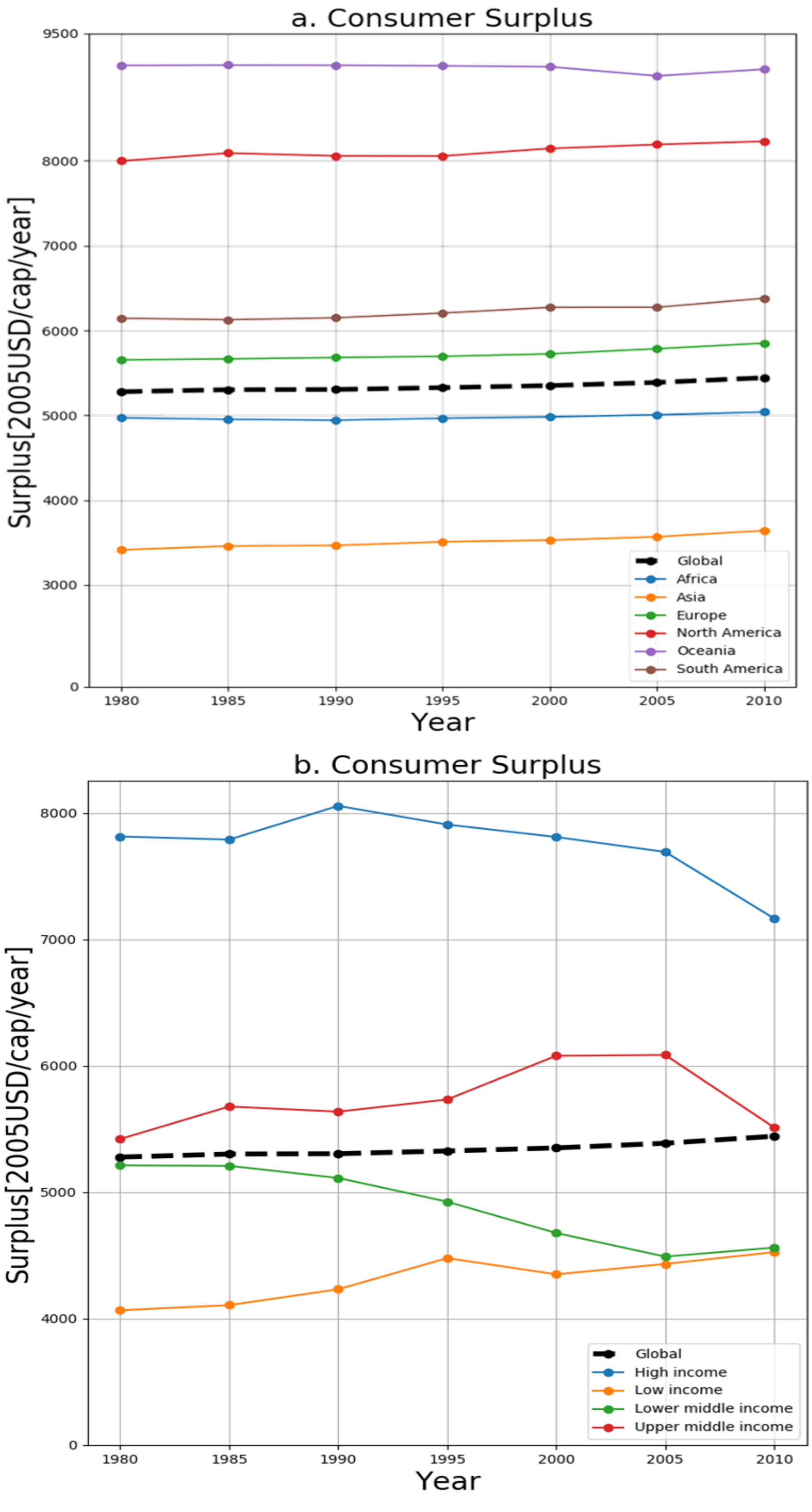


Fig 4.13. Consumer surplus [2005USD/cap] **a.** Continental consumer surplus, **b.** World Bank income category consumer surplus. (Black dash line is Global consumer surplus).

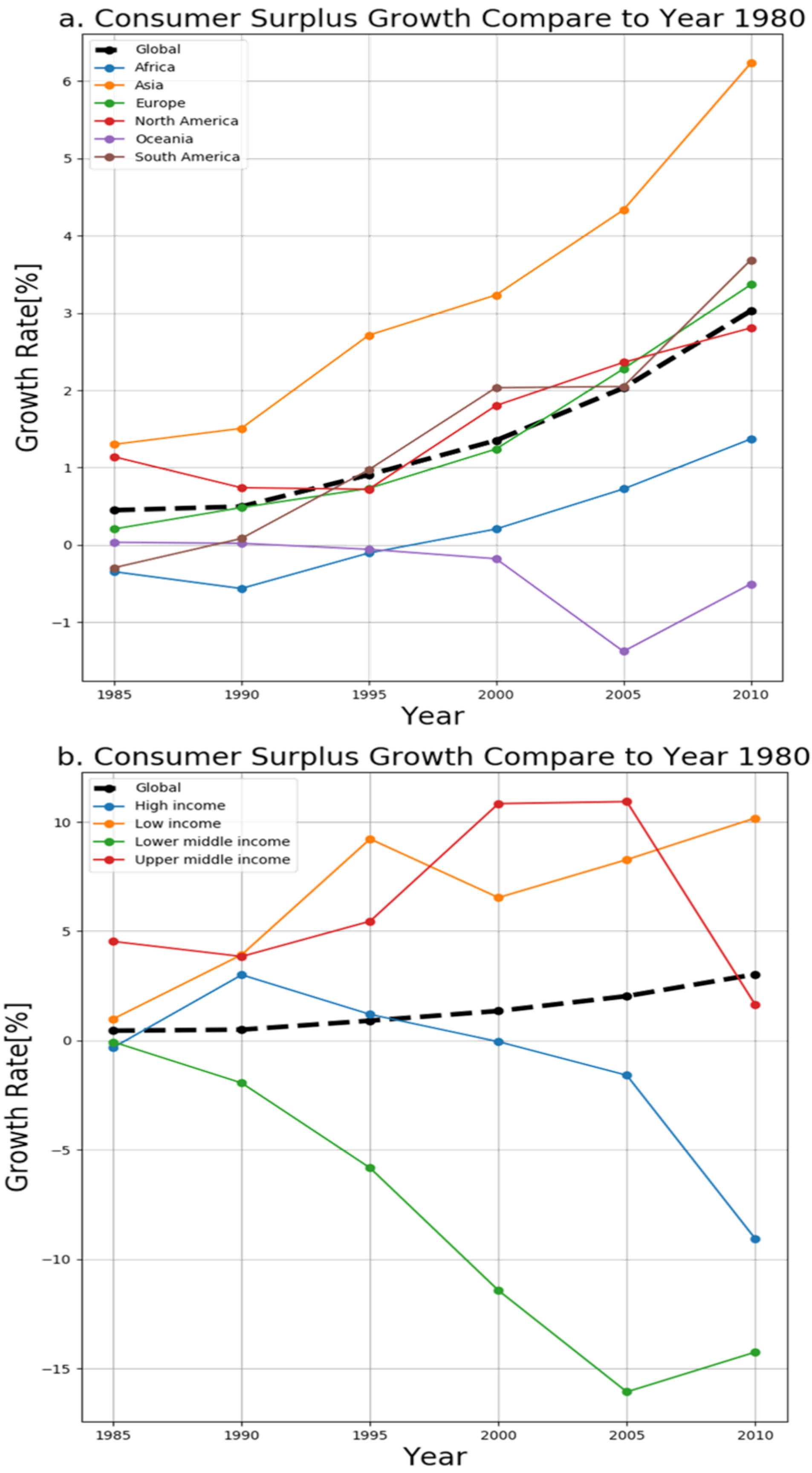


Fig 4.14. Consumer surplus Growth Rate Compare to the year 1980; **a.** Continental, **b.** World Bank income category. (Black dash line is Global consumer surplus growth rate).

Table 4-9. The continental total economic surplus in trillion USD

Continent	Total Surplus [trillion USD]						
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**
Africa	1.87	2.13	2.29	2.69	2.99	3.49	3.98
Asia	7.41	8.42	9.20	10.07	11.01	11.65	12.67
Europe	3.58	3.65	3.71	3.78	3.85	3.92	3.94
North America	3.61	3.89	4.12	4.45	4.76	4.98	5.21
Oceania	0.20	0.22	0.23	0.25	0.27	0.30	0.32
South America	1.30	1.44	1.60	1.78	1.94	2.03	2.22
Global	17.98	19.74	21.17	23.03	24.82	26.37	28.35

The total economic surplus in each content is calculated by summing total economic surplus ($) of each grid within the continent, not by multiplying population to economic surplus ($/cap) of each continent (table 4.7 and figure 4.13 a).

4.4 CONCLUSION

There are number of studies that focus on global domestic water withdrawal (Alcamo et al., 2003; Flörke et al., 2013; Hanasaki et al., 2013a; Hejazi et al., 2013; Shen et al., 2008; Shiklomanov, 2000; Wada, Gleeson, et al., 2014; Wada, Wisser, et al., 2014). They estimated past and future domestic water withdrawal, but their estimation was on the country or regional scale. Estimation in a more small scale is essential to get more accurate result due to using country average value can hide real value in small scale (Gleick, 1996). For example, in the United States, domestic water intensity in the western area is higher than in the eastern region (Rockaway et al., 2011). Also because of water supply efficiency difference in an urban and rural area, domestic water consumption is different (Hejazi et al., 2013), but this kind of situation will be hidden in global estimation in-country or regional scale, so this study tries to estimate domestic water withdrawal in grid-scale for the first time. Our model fitting result (Willmott index) shows that model performance is fine in almost all of the world. Finally, we could construct both domestic water withdrawal (DWW) and domestic water intensity for a global scale at the grid level from1980 to 2010. Our result shows DWW increased 2.3 times from 201 to 469 km^3yr^{-1}, from 1980 to 2010, with an annual growth rate of 1.9%. The highest growth rate captured in Asia and South America. Also, Our result shows that in 1990 1.43 billion people suffered to access basic human required amount compared to 1 billion people of Glick (Gleick, 1996), although this number is decreasing to almost 660 million in 2010 (section 4.3.1).

Lack of input data is the limitation of this approach, so we prepare input data with a unique method (section 4.2.1). In this study we examined the impact of economic development in DWW; therefore we didn't consider climate condition and seasonal variation, while variation of temperature can affect to human water demand (Wada, Van Beek, Viviroli, et al., 2011) and it can reach the highest and lowest level in summer and winter respectively (Mitchell & Jones, 2005). Since we believe that technological improvement is included in the historical record (mostly it can be seen in developed countries' historical trend), so we didn't involve technology improvement as an extra parameter because it can cause underestimations.

Finally, an economic assessment of domestic water is estimated for the first time on a global scale over the grid level. This study used the same methodology to all countries (grid cells) with the different economic situation, although it can be debated (Neverre & Dumas, 2015) (section 4.2.3). The global economic value of domestic water use is just increased 3% from 5278 to 5443 $\$yr^{-1}yr^{-1}$ with $0.1\%yr^{-1}$ growth rate from 1980 to 2010. Oceania and High-income countries have the highest and Asia, and low-income countries have the lowest economic value of domestic water use, since the economic value in Africa and Asia as continental scale, and low and lower middle income countries as income category, is smaller than global average value. It is noted that global total domestic water use economic value increased by 58%, and from almost 18 trillion USD in 1980 reached 28 trillion USD in 2010 (table 4.9). However, in some African countries which didn't reach to basic water requirement (18.25 m^3/year/cap) due to the adverse impact of high water pricing, the economic value was higher than in developed countries. In general, the economic value of domestic water is far higher in developed countries compared to developing countries (section 4.3.2).

With the calculation of other sectors' economic value, e.g., agriculture and industry, we can build up a more efficient allocation policy to maximize the economic profit of water use (Bierkens et al., 2019) to reduce water shortage pressure. This study can be applied for future projection of DWW, DWWC, and associated economic value. In this study, we didn't consider cost of extracting water as supply-side cost, since due to groundwater depletion and shortage of water availability, water extraction cost will increase (Foster et al., 2015), and it can affect on economic value as a result of increasing water tariff, therefore considering supply-side cost parameters can increase accuracy of future economic assessment of water use (Bierkens et al., 2019). This framework can be applied in regional and small scale with more details which have been neglected in global scale analysis

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Chapter 5: Synthesis

5.1 INTRODUCTION

Up to now, the economic value of water use in different sectors is calculated. This chapter tries to make a synthesis of other sections' results, with a comparison of the economic value of different sectors in the global average and also at the country scale. In a reallocation policy, it is crucial to have an integrated framework of economic benefit for all sectors (Bierkens et al., 2019), and water allocates to different sectors based on their capability of economic value production (Harou et al., 2009). Finally, this chapter tries to show how much total economic benefits are produced by using water in a human being's life for 30 years from 1980 to 2010. Since this chapter doesn’t have any specific method for calculations, hence there is no methodology section.

5.2 OBJECTIVE

This chapter tries to summarize another chapter’s output and make a comparison for understanding:

- Which sector has more economic value in term of unit amount of water (USD/m³).
- Calculating total economic value (USD) made by water use in all sectors for 30 years from 1980 to 2010.

5.3 RESULT

Figure 5.1 shows the global average of the economic value of water intensity (USD/m³) for different sectors (agriculture, industry, and domestic) from 1980 to 2010. For the agriculture sector, the average shadow price of four crops (maize, rice, soy, and wheat) is taken. Table 5.1 shows the global average of economic value for deferent sectors from 1980 to 2010 in numbers.

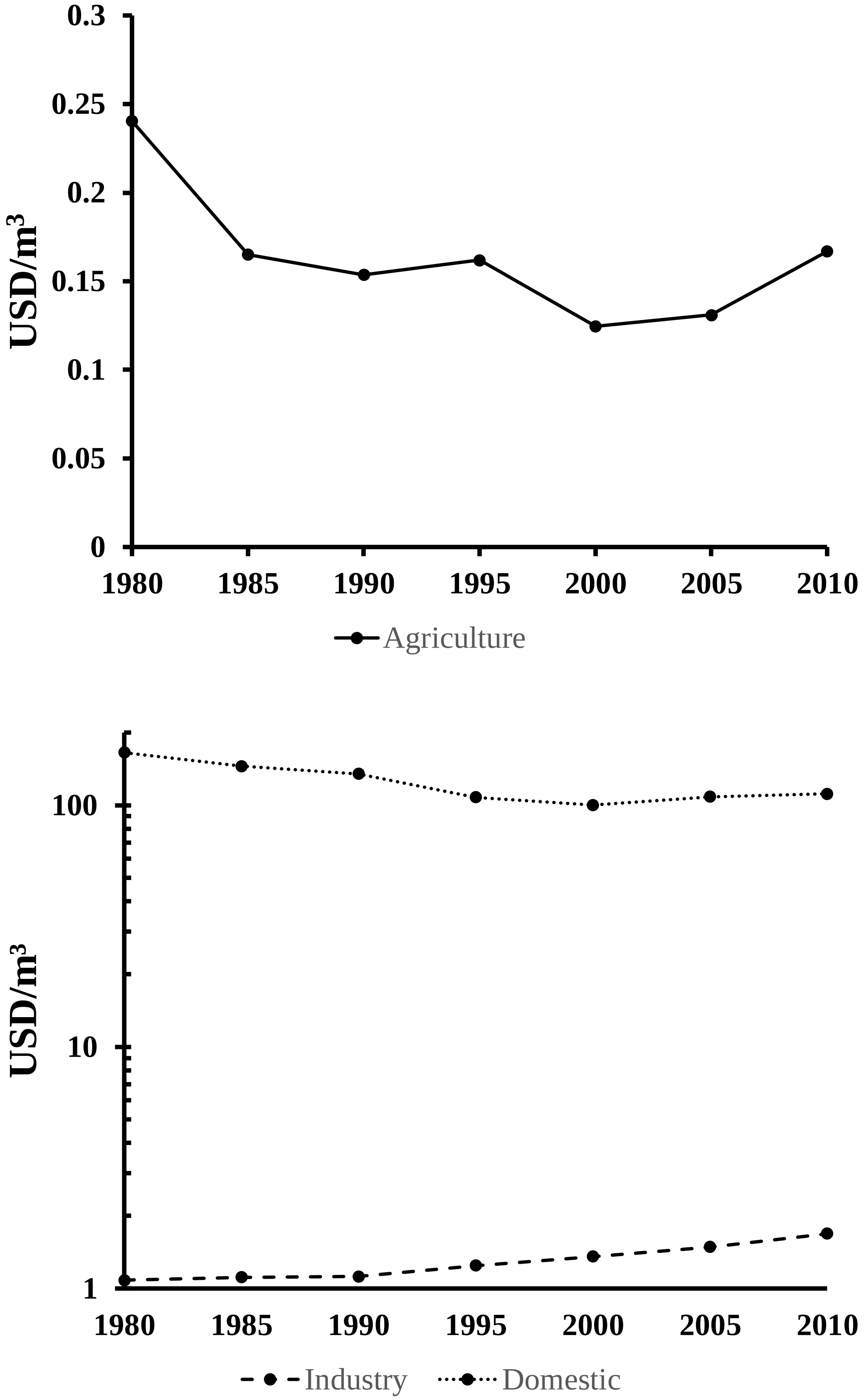


Fig 5.1. The global annual average of the economic value of water intensity (USD/m³) for different sectors (agriculture, industry, and domestic) from 1980 to 2010.

Table 5-1. Global annual average of the economic value of water intensity (USD/m³) for different sectors and global average from 1980 to 2010.

	1980	1985	1990	1995	2000	2005	2010	Average
Agriculture	0.24	0.17	0.15	0.16	0.12	0.13	0.17	0.16
Industry	1.08	1.11	1.12	1.24	1.36	1.48	1.68	1.30
Domestic	165.1	145.0	134.9	107.9	100.2	108.4	111.4	124.7

The economic value of DWW is far above the IWW and agriculture. Agriculture water value is minimal (less than 1 USD/m³) compare to others. IWW economic value is continuously increasing, but for agriculture, it is decreasing, and after 2000, it grows up. For DWW from 1980 to 2000, in most of the developed countries after reaching saturation point, DWW starts to decline; as a result, economic value is also decreasing. After 2000, with economic growth in developing countries, both DWW and economic value increases.

As explained in chapter four, DWW was divided to three categories (high, medium and low essential), and economic value is shown here (figure 5.1 and table 5.1) is the average of all types of DWW, therefore when the economic value of each category is calculated separately, it could be lead to different results. Figure 5.2 and Table 5.2 shows the economic value of each group. The first category (the most essential) has a very high economic value (the 30 years average is almost 330 USD/m³). For the second and third categories (intermediate and low essential respectively), the amount of reduction is impressive. The second and third categories have almost 10 and 3 USD/m³, respectively.

Additionally, the economic value of the first category is decreasing during the time while it is increasing for the second and third categories at the same time. The rate of decline for the first category is 0.7%, with an average annual decrease of 0.02%. For the second and third groups, the growth rate is almost 12% and 6%, with an average yearly growth of 0.41% and 0.2% for 30 years.

Decreasing economic benefit in the first category indicates that in some countries in this category, DWW is decreasing even though their water use is less than basic human need (18.25 m³/cap/year). The highest growth rate in the second category shows the efforts of different countries to reach the optimum level of water use. For the third category, with increasing wealth in some countries, water use has reached a saturated point, and It may have fallen in some developed countries.

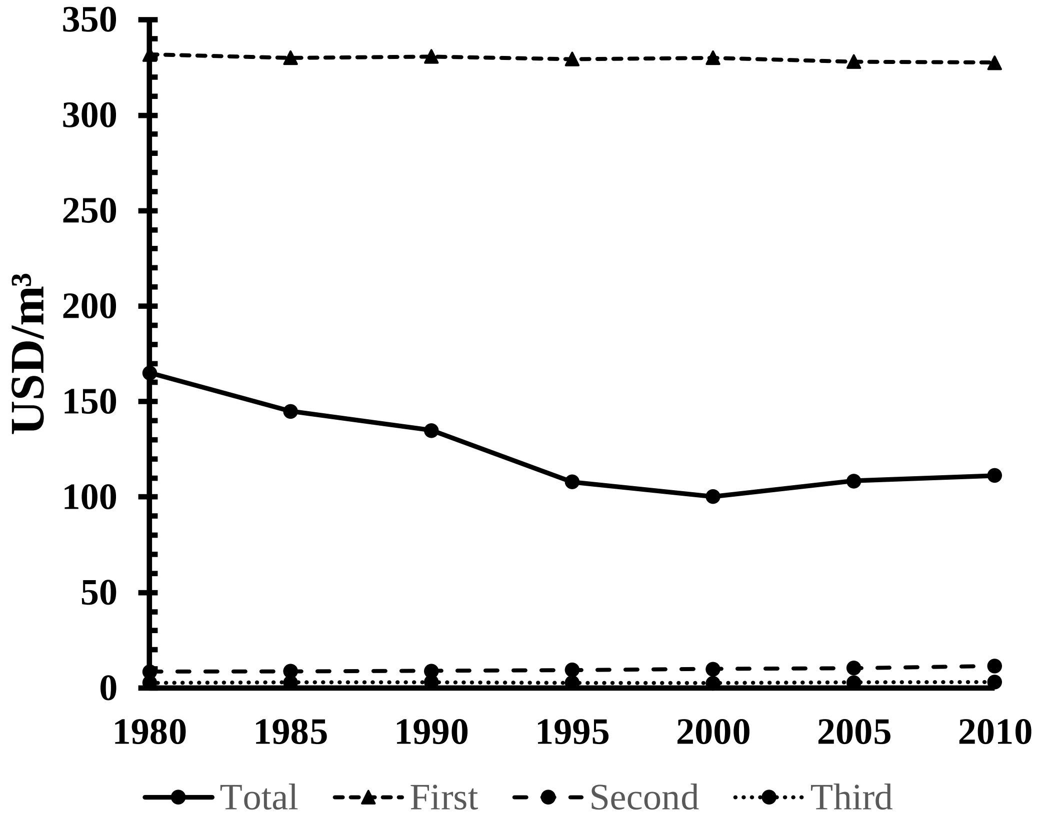
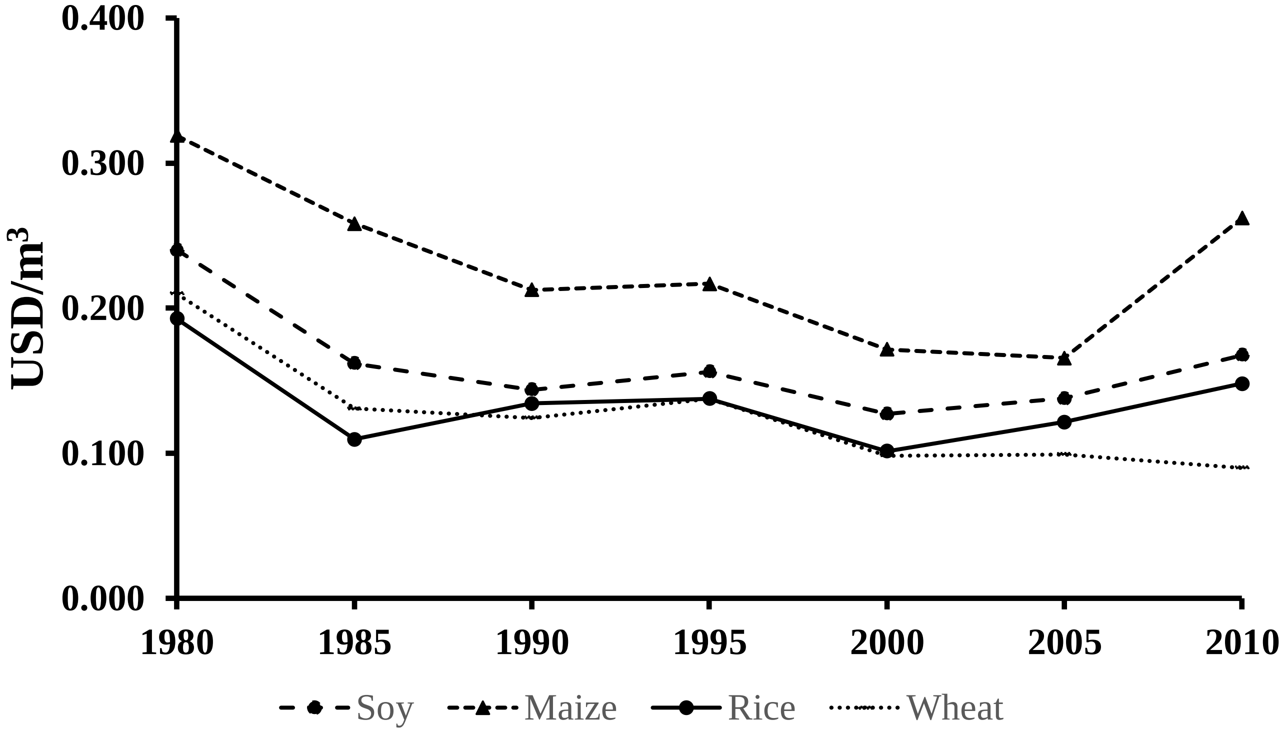


Fig 5.2. The global average of economic vale (USD/m³) in the domestic sector for different categories (First is high, second is medium, and third is low essential categories).

Table 5-2. Global average of economic vale (USD/m³) in the domestic sector for different categories and global average from 1980 to 2010.

	1980	1985	1990	1995	2000	2005	2010	Average
Total	165.1	145.0	134.9	107.9	100.2	108.4	111.4	124.7
First	331.9	330.1	330.7	329.4	330.0	328.1	327.6	329.7
Second	8.6	8.8	9.0	9.4	10.0	10.4	11.5	9.7
Third	2.7	2.97	3.04	2.7	2.6	2.9	3.1	2.9

Figure 5.3 shows the economic value of the second and third parts of DWW, IWW, and each crop in the agriculture sector in the global average.



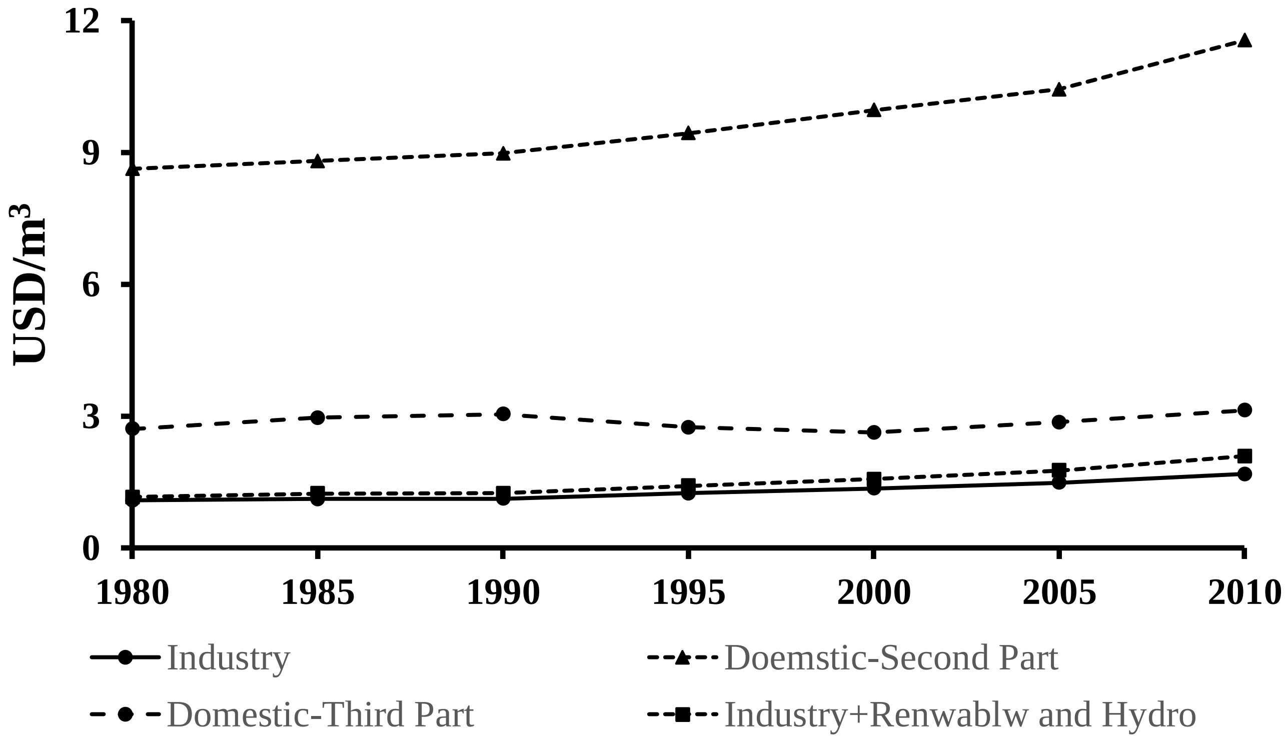


Fig 5.3. The global annual average of economic value for the second and third parts of DWW, IWW, and each crop (USD/m³).

As explained, the first part of DWW has a very high economic value. Therefore, it can be at the top priority in the water allocation policy, and according to its definition (basic human demand), it seems logical. Based on figure 5.3, the IWW value is less than the second and third parts of DWW. After 1990, the economic value of the 3rd part and IWW is getting closer; also, their growth rate is almost at the same level. Still, the economic value of the third part is almost two times higher than the IWW economic value. By considering hydropower and renewable energy, IWW economic value is increasing, but still, it is less than 3rd part of DWW. The economic value of agriculture products is still much less than the rest. In these comparisons, there are some points to consider;

1. Global average value can be different at the country or grid scales.
2. The economic valuation method for each sector is different. Applying demand function method to other sectors (agriculture and industry) is required for a more precise direct comparison of the economic value of various areas since economic value varies for the different quantity (demand function), which is neglected in agriculture and industry sectors analysis. However, unlike DWW, water is the opportunity cost of final products in the agriculture and industry sectors.
3. Total cost opportunity should be considered for all sectors; this means that agriculture may have a low value, but it has more potential to add economic benefits in total since it has the biggest global share.

According to these contents, domestic sectors have the highest, and agriculture has the lowest value in terms of the global average of economic value.

Figure 5.4 -6 shows the total economic benefit of water use (USD) at a global scale from 1980 to 2010. Figure 5.4 includes all sectors, but for figure 5.5 and 5.6, the first part of DWW is excluded for more even-handed comparison.

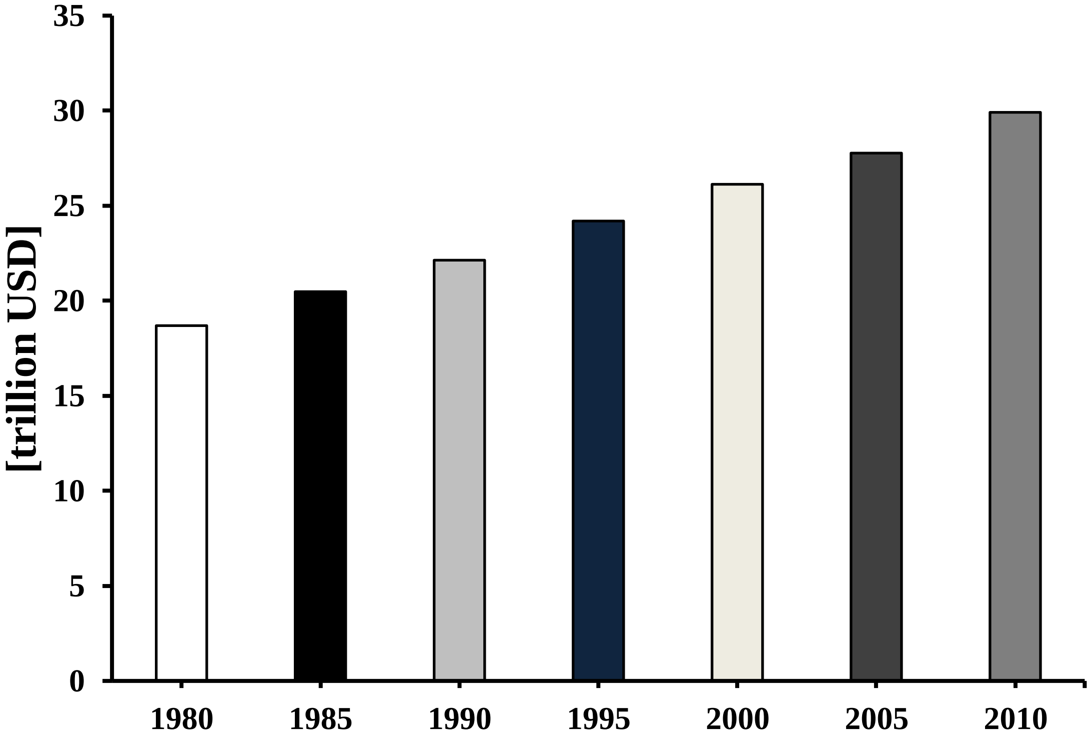


Fig 5.4. Total economic benefit of water use for all sectors on the global scale (trillion USD).

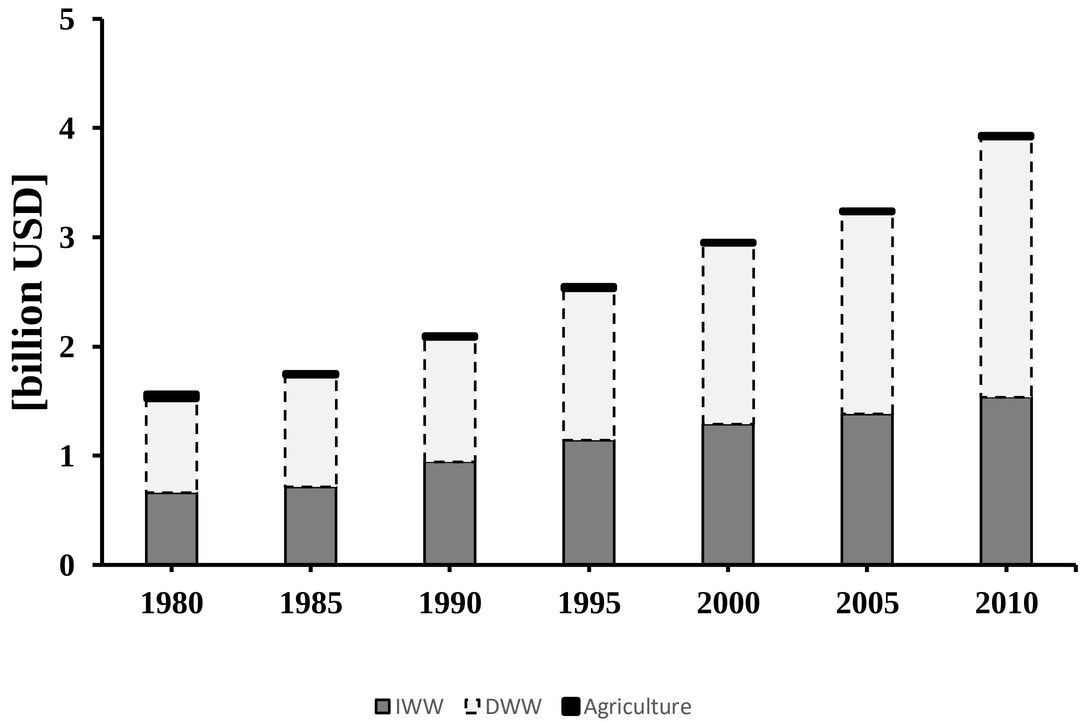


Fig 5.5. Partitioning of the total economic benefit of water use for all sectors (excluding the first part of DWW) on the global scale (trillion USD).

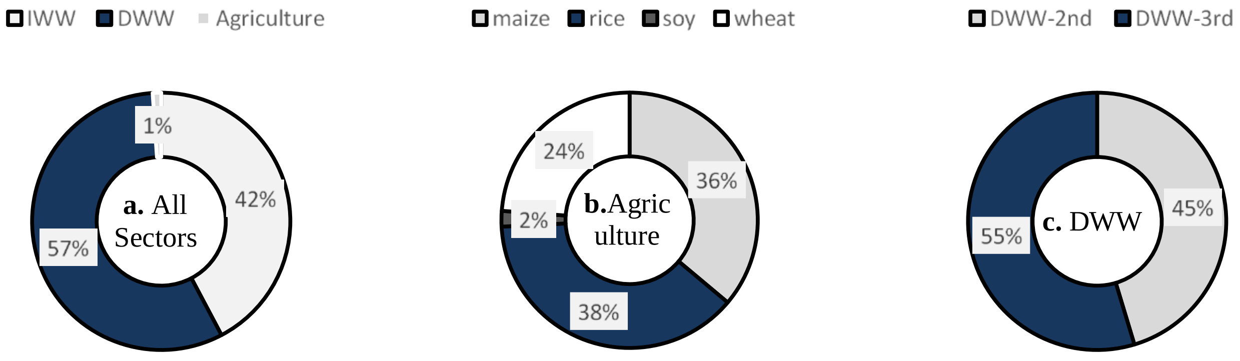


Fig 5.6. Partitioning share of global 30 years average of total economic benefit. a. for all sectors (excluding the first part of DWW), b. for the agriculture sector, and c. for the domestic sector (excluding the first part).

In terms of total economic benefits (figure 5.4), the profit increases by 60 percent during 30 years (from almost 19 trillion USD to nearly 30 trillion USD), while the total global GDP increases 280 percent, from 18 to 68 trillion USD. As mentioned, the first part of DWW has very high economic value; therefore, it is excluded for a better comparison of economic benefit for the different sectors (figure 5.5 and 5.6). As we said, a direct comparison of economic value in different sectors is not accurate enough when the valuation method is different for the various sectors, but still, it is useful. The agriculture sector has a meager rate share (figure 5.5 and 5.6 a), and it is only 1% in 30 years average of global share (figure 5.6 a). In terms of different crops, rice has the highest, and soy has the lowest percentage. The shadow price of maize is higher than rice (almost 1.65 times higher in terms of 30 years average), and crop price of maize is cheaper (approximately 1.4 times lower for long term average); therefore, it can indicate that maize cultivation efficiency or cultivation area is higher than rice. The total economic benefit of DWW in higher than IWW for all the time (figure 5.5) and more than half of overall economic benefits belong to DWW for 30 years globally (figure 5.6 a). the third part of DWW has a higher sharing rate compared to the second part (figure 5.6 c). Although the second part has a higher value per cubic meter, the higher water withdrawal for the third part compensates the economic value effect, and thus the third part has a higher value in terms of total.

5.4 CONCLUSION

This chapter summarized all other chapters' results and made simple comparisons over the globe for each sector separately and all together in terms of per cubic meter and total.

The economic value of DWW is far above the IWW and agriculture, and agriculture water value is minimum (agriculture =0.16 USD/m³, IWW = 1.3 USD/m³ and DWW = 124.7 USD/m³ for long term average). Among DWW components, the first par has the highest (330 (USD/m³) for long term average), and other parts value is less than 10 (USD/m³) in terms of 30 years average. IWW economic value is less than the 2nd and 3rd part of DWW; also, the economic value of agriculture products are meager in comparison to IWW and DWW. Within countries, in general, developed countries have the highest value.

Human activities in all water sectors make almost 30 trillion benefits globally in 2010, although this value is still 2.3 times less than the global GDP in 2010, it shows the importance of water for human life. Total economic benefit increases 1.6 times for 30 years.

Agriculture has the lowest value, but the amount of food needed to survive should have a high price in terms of willingness to pay. Therefore with different valuation methodologies, it is difficult to assess all sectors together, and we need a more integrated method for valuation. Future assessment is absent in this chapter as same as others.

Chapter 6: Conclusions and Future Work

6.1 CONCLUSIONS

The main objective of the current framework is the valuation of global water use in economic terms from 1980 to 2010 as the past to the current situation. The three sectors (agriculture, industry, and domestic) are selected as the primary source of water use. Assessments are divided into two parts for each sector: 1) Calculating water withdrawal at grid scales (for industry sector only for a total term) 2) Calculating the economic value of water based on water demand (water withdrawal).

The shadow price of water is calculated as the economic value of water in the agriculture sector for four major crops, maize, rice, soy, and wheat. The yield comparison approach is applied as a marginal added value by irrigation for calculating shadow price. Maize has the highest, and wheat has the lowest value. In terms of long term average shadow price is; maize = 0.22, soy = 0.16, rice = 0.13 and wheat = 0.13 USD/m³. The economic value of agriculture productions is below 1 USD/m³.

Both H08 and WaterGAP methods are applied for calculating IWW since H08 has better performance (Willmott Index); economic analysis is carried out over its output. The economic value for IWW is calculated by comparison with desalination technology. IWW (km³/year) increases by almost 50% during the 30 years from 610 to 913 km³. Also, industrial water intensity (m³/MWh/year) is decreased, and it halved at the same time. IWW economic value increases 1.6 times from almost 1.1 to 1.7 (USD/m³) during 30 years. The total economic value of IWW is calculated over the grid level as potential economic value. The global average total economic value of IWW is continuously growing up, and from 660 billion USD in 1980, it reaches 1537 billion USD in 2010, which means economic value increases almost 2.3 times, with average annual growth of 4.4%. Application of hydropower and renewable energy increased by 13% and 1% of the economic value of IWW (USD/m^3) during the 30 years, respectively. Also, the total economic value increased, and the overall global economic benefits increased by 24% and reached nearly 1900 billion USD in 2010.

DWW is calculated on the grid-scale by the revised WaterGAP model. DWW increases 2.3 times from 201 to 469 km³yr^{-1}, from 1980 to 2010, with an annual growth rate of 1.9%. Also, our result shows that in 1990, 1.43 billion people suffered to access basic human required amount, although this number is decreasing to almost 660 million in 2010. By building up the demand function, economic value is calculated at grid scales. The global economic value of domestic water use increases by 3% from 5278 to 5443 $\$yr^{-1}yr^{-1,}$ with a $0.1\%yr^{-1}$ growth rate from 1980 to 2010. Global total domestic water use economic value increased by 58%, and from almost 18 trillion USD in 1980 reached 28 trillion USD in 2010.

The economic value of DWW is far above the IWW and agriculture, and agriculture water value is minimum (agriculture =0.16 USD/m^3, IWW = 1.3 USD/m^3 and DWW = 124.7 USD/m^3 for long term average).

6.2 FUTURE WORK

The economic value of the water concept can be used for allocation policy. Therefore it can apply for dam regulation rules to regulate dam output based on the economic value that water can produce for each sector. It this case, we need to evaluate the economic value of water with the same methodology (i.e., applying demand function to all sectors) since the range of economic value varies for different methods.

Combining this study result with available water and calculating economic losses for water scarcity is also essential. It is possible to examine the impact of some extreme events, i.e., El Niño, La Niña, and drought in human economic activities based on the economic value of water that can't meet human demand.

In this research, future assessments are absent. Projecting future situations are in high demand based on different scenarios (SSPs, RCPs, etc.) for the short and long term.

Despite its importance, economic terms still have not got enough attention to water resource topics and agenda. This framework is a small and essential step towards opening an important concept that will be received a lot of attention in the future.

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Appendices

Appendix A Country ISO3 Code

ISO3	Country	ISO3	Country	ISO3	Country
AFG	Afghanistan	**GIN**	Guinea	**NOR**	Norway
AGO	Angola	**GMB**	Gambia	**NPL**	Nepal
ALB	Albania	**GNB**	Guinea-Bissau	**NRU**	Nauru
AND	Andorra	**GNQ**	Equatorial Guinea	**NZL**	New Zealand
ARE	United Arab Emirates	**GRC**	Greece	**OMN**	Oman
ARG	Argentina	**GRD**	Grenada	**PAK**	Pakistan
ARM	Armenia	**GTM**	Guatemala	**PAN**	Panama
ATG	Antigua and Barbuda	**GUY**	Guyana	**PER**	Peru
AUS	Australia	**HND**	Honduras	**PHL**	Philippines
AUT	Austria	**HRV**	Croatia	**PNG**	Papua New Guinea
AZE	Azerbaijan	**HTI**	Haiti	**POL**	Poland
BDI	Burundi	**HUN**	Hungary	**PRK**	Korea, Democratic People's Republic of
BEL	Belgium	**IDN**	Indonesia	**PRT**	Portugal
BEN	Benin	**IND**	India	**PRY**	Paraguay
BFA	Burkina Faso	**IRL**	Ireland	**PSE**	Palestinian Territory, Occupied
BGD	Bangladesh	**IRN**	Iran, Islamic Republic of	**QAT**	Qatar
BGR	Bulgaria	**IRQ**	Iraq	**ROU**	Romania
BHR	Bahrain	**ISL**	Iceland	**RUS**	Russia Federation
BHS	Bahamas	**ISR**	Israel	**RWA**	Rwanda
BIH	Bosnia and Herzegovina	**ITA**	Italy	**SAU**	Saudi Arabia
BLR	Belarus	**JAM**	Jamaica	**SDN**	Sudan
BLZ	Belize	**JOR**	Jordan	**SEN**	Senegal
BOL	Bolivia	**JPN**	Japan	**SGP**	Singapore
BRA	Brazil	**KAZ**	Kazakstan	**SLB**	Solomon Islands
BRB	Barbados	**KEN**	Kenya	**SLE**	Sierra Leone
BRN	Brunei Darussalam	**KGZ**	Kyrgyzstan	**SLV**	El Salvador
BTN	Bhutan	**KHM**	Cambodia	**SMR**	San Marino
BWA	Botswana	**KIR**	Kiribati	**SOM**	Somalia
CAF	Central African Republic	**KNA**	Saint Kitts & Nevis	**SRB**	Serbia
CAN	Canada	**KOR**	Korea, Republic of	**STP**	Sao Tome and Principe
CHE	Switzerland	**KWT**	Kuwait	**SUR**	Suriname
CHL	Chile	**LAO**	Lao, People's Democratic Republic	**SVK**	Slovakia
CHN	China	**LBN**	Lebanon	**SVN**	Slovenia
CIV	Cote d'Ivoire	**LBR**	Liberia	**SWE**	Sweden
CMR	Cameroon	**LBY**	Libyan Arab Jamahiriya	**SWZ**	Swaziland
COD	Congo, The Democratic Republic of	**LCA**	Saint Lucia	**SYC**	Seychelles
COG	Congo	**LIE**	Liechtenstein	**SYR**	Syrian Arab Republic
COL	Colombia	**LKA**	Sri Lanka	**TCD**	Chad
COM	Comoros	**LSO**	Lesotho	**TGO**	Togo
CPV	Cape Verde	**LTU**	Lithuania	**THA**	Thailand
CRI	Costa Rica	**LUX**	Luxembourg	**TJK**	Tajikistan
CUB	Cuba	**LVA**	Latvia	**TKM**	Turkmenistan
CYP	Cyprus	**MAR**	Morocco	**TLS**	Timor-Leste
CZE	Czech Republic	**MCO**	Monaco	**TON**	Tonga
DEU	Germany	**MDA**	Moldova, Republic of	**TTO**	Trinidad and Tobago
DJI	Djibouti	**MDG**	Madagascar	**TUN**	Tunisia
DMA	Dominica	**MDV**	Maldives	**TUR**	Turkey
DNK	Denmark	**MEX**	Mexico	**TUV**	Tuvalu
DOM	Dominican Republic	**MHL**	Marshall Islands	**TZA**	Tanzania, United Republic of
DZA	Algeria	**MKD**	Macedonia, The Former Yugoslav Republic Of	**UGA**	Uganda
ECU	Ecuador	**MLI**	Mali	**UKR**	Ukraine
EGY	Egypt	**MLT**	Malta	**URY**	Uruguay
ERI	Eritrea	**MMR**	Myanmar	**USA**	United States
ESH	Western Sahara	**MNE**	Montenegro	**UZB**	Uzbekistan
ESP	Spain	**MNG**	Mongolia	**VAT**	Holy See (Vatican City State)
EST	Estonia	**MOZ**	Mozambique	**VCT**	Saint Vincent and the Grenadines
ETH	Ethiopia	**MRT**	Mauritania	**VEN**	Venezuela
FIN	Finland	**MUS**	Mauritius	**VNM**	Vietnam
FJI	Fiji	**MWI**	Malawi	**VUT**	Vanuatu
FRA	France	**MYS**	Malaysia	**WSM**	Samoa
FSM	Micronesia, Federated States of	**NAM**	Namibia	**YEM**	Yemen
GAB	Gabon	**NER**	Niger	**ZAF**	South Africa
GBR	United Kingdom	**NGA**	Nigeria	**ZMB**	Zambia
GEO	Georgia	**NIC**	Nicaragua	**ZWE**	Zimbabwe
GHA	Ghana	**NLD**	Netherlands		