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Invention and diffusion of water supply and water efficiency technologies: Insights from a global patent dataset

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Abstract

This paper identifies over 50 000 patents filed worldwide in various water-related technologies between 1990 and 2010, distinguishing between those related to availability (supply) and conservation (demand) technologies. Patenting activity is analysed – including inventive activity by country and technology, international diffusion of such water-related technologies, and international collaboration in technology development. Three results stand out from our analysis. First, although inventive activity in water-related technologies has been increasing over the last two decades, this growth has been disproportionately concentrated on supply-side technologies. Second, whilst 80% of water-related invention worldwide occurs in countries with low or moderate water scarcity, several countries with absolute or chronic water scarcity are relatively specialized in water efficiency technologies. Finally, although we observe a positive correlation between water scarcity and local filings of water patents, some countries with high water availability, in particular Switzerland or Norway, nevertheless appear as significant markets for water-efficiency technologies. This suggests that drivers other than local demand, like regulation and social and cultural factors, play a role in explaining the global flows of technologies. And finally, the extent to which innovation is "internationalised" shows some distinct patterns relative to those observed for innovation in technologies in general.

JEL codes: O31; Q25; Q55

Keywords: water security; resource scarcity; invention; international technology diffusion.

1. Introduction

The intensity of human appropriation and use of freshwater have been widely considered as generating a global water crisis. The crisis has physical dimensions, namely problems of availability, quality and hazard; as well as social, political and economic dimensions associated with issues such as basic human needs, equity, institutional capacity and investment. The challenge of increasing water scarcity and resulting competition for water driven by growth in population and consumption, have been key in generating concern about global water security. This is compounded by the threat of climate change, with higher temperatures, sea level rise and precipitation variability affecting water availability in many areas of the world, particularly dry subtropical regions (IPCC WGII, 2014). In an analysis of climate change scenarios from 21 Global Climate Models, across four socio-economic and emissions scenarios, and with two different measures of water scarcity[1], Gosling and Arnell (2013) estimate that by 2050, between 0.5 and 3.1 billion people could be exposed to increased water scarcity due to climate change. Scarcity is manifest in situations where societal and environmental requirements exceed either physical availability or the economic and institutional capacity to harness sufficient water. Pathways of transition in societal water use such as river basin trajectories (Molle et al., 2010) have been defined which describe shifting patterns of water use and management as the difference between supply and demand diminishes, moving from exploitation through conservation to supply augmentation (Keller et al., 1998). Gleick (2003) sets out the elements of a "soft path" transition that complements large-scale centralized physical infrastructure with lower cost

[1] The Water Crowding Index (WCI) and the Water Stress Index (WSI).

community-scale systems, decentralized and open decision-making, water markets and equitable pricing, and environmental protection.

Whilst such factors are likely to be central to resolving the water crisis, there is no doubt that technology will also play an important role in addressing global water security challenges, and that is the subject of this paper. Addressing the challenges associated with water scarcity will necessitate greater deployment of water-related technologies, including drip irrigation, drought-resistant crops, rainwater collection, grey-water reuse and water-saving devices for residential water supply. For this reason, invention and technology diffusion are essential for the successful management of water scarcity challenges. The development and deployment of water conservation and availability technologies should therefore be a priority for public policies directed at maximising a sustainable contribution from water-related activities to economic development.

Against this background the objective of this paper is to inform the debate with factual evidence on the geographic distribution and global diffusion of water-related inventions. It provides the first empirical review of the development and international diffusion of water-related technologies at the global level, based on a unique dataset of patent applications filed between 1990 and 2010. We focus on water availability and consider a wide range of technologies that address supply-side approaches (rainwater collection, groundwater collection, water storage, desalination…) or demand-side approaches (water control in agriculture, water efficiency technologies in power production, domestic water recycling, efficient water distribution systems…). In the paper, such technologies are referred to as water-related technologies, distinguishing between those relevant for availability (supply) and conservation (demand).

We use patent applications as an indicator of invention activity and of international technology diffusion. Our dataset is drawn from the *EPO World Patent Statistical Database* (PATSTAT), from which a new patent data set has been generated that includes over 50,000 patents filed worldwide in various water-related technologies between 1990 and 2010 (this represents less than 0.2% of all inventions patented worldwide during this period). While in some sense patents are an imperfect proxy for invention and technology diffusion (and we discuss these limitations at length in the next section), the richness of the information available in patent data (such as the precise description of the technology covered, the country in which the patent is filed, the date of application, the location of inventors…) allows for an in-depth analysis of inventive activity, international diffusion of technologies, and international collaboration in research. No other source of data – e.g., research and development expenditures – would allow for the development of invention-related indicators which are commensurable across years and countries.

Identifying relevant patent documents in all water-related technologies in a robust manner is a difficult task, and for this reason the study is necessarily limited in scope. Omitted technologies include water treatment technologies or others directed at "water quality" issues (rather than water quantity)[2] and invention in sectors that are not directly water-related but might contribute to improved water management and water efficiency (e.g. ICT, new materials). Nevertheless, the analysis covers most of the technological adaptation options for water supply and demand identified by a recent overview in the context of climate change (see Jiménez Cisneros et al., 2014).

[2] See OECD (2011a) and Johnstone et al. (2012) for analyses of technological innovation related to "water quality".

The study builds upon two strands of the literature. First, it builds on the growing empirical literature that uses patent data to describe the geography of environmental invention and explain its determinants (Dechezleprêtre et al., 2011; Haščič and Johnstone, 2011; Lanjouw and Mody, 1996; OECD, 2011a; OECD, 2012a; Popp, 2006; Popp, 2011; Verdolini and Galeotti, 2011). However, the focus of this literature has been almost exclusively on climate change mitigation invention, such as renewable energy technologies or low-carbon transportation. In contrast, to the best of our knowledge no empirical analysis has been carried out so far on water supply- and efficiency-related inventions.

Second, the paper relates to the vast literature on water management, recently surveyed in Convery (2013). (See also Olmstead, 2010; OECD, 2010 and OECD, 2012b.) This literature has mainly investigated the role of governance structures in addressing problems of water scarcity, with a strong focus on the role of market-based policies that may induce a more sustainable consumption of water resources, for example the creation of water markets. The role of invention and diffusion of water-related technologies is only addressed parenthetically in this literature. The role of science includes the importance of water institutions alongside advances in technology like treatment for drinking and wastewater, storage and transport facilities, and science for managing water for agricultural and environmental purposes (Jury and Vaux, 2005). Wehn and Montalvo (2014) argue that whilst Europe is held to be a leader in knowledge, technology and innovation in water, the sector in general is perceived to be less dynamic and innovative than many other sectors. Water utilities generally rely on outside actors, either research institutions or supply chain companies, to perform research and deliver pre-tested advances (Speight, 2015). US water utilities do not directly allocate budget line items for research and this coupled with their diversity of size and types means estimates for US research investment are difficult to make. UK water companies invest just over one half of one percent of their capital expenditures on research and development (Speight, 2015). Recent policies in the EU seek to address the key barriers in water markets, such as insufficient access to financing for innovation, high capital-intensity, and built-in risk aversion (EIP, 2014).. Comparison of privately owned companies (in the UK) and publicly owned utilities (US municipal utilities) shows drivers of innovation in the water industry include: 'a supportive culture at the water utility; a regulatory regime that allows or even promotes innovation; the financial ability to undertake research and implement improvements; and crucially, the backing of the public' (Speight, 2015, abstract).

We seek to address the following key questions. What is the pace of water-related innovation? Where does the development of water inventions take place? What is the contribution of innovators located in developing countries, in particular in water-scarce places? To what extent is technology being transferred to countries facing water scarcity issues? Are these countries well connected with international research networks and global knowledge flows? Is invention in the water sector different from other technology areas?

Given the increasing population and demand for water, we expect patent applications for technologies related to water availability to have increased over time. However, as reported in recent literature there has been an increasing emphasis on demand-side solutions to water scarcity, and as such we expect to find relatively higher rates of patent applications than for supply-side approaches. Simple economic reasoning suggests that water-scarce countries should attract more patent filings for water supply and water efficiency. However, water-scarce countries may lack the research and development infrastructure to develop cutting-edge technologies that typically get patented.

The remainder of this paper is organized as follows. Section 2 briefly presents how the patent system works and discusses the advantages and limitations of using patents as indicators of invention and technology diffusion. Section 3 presents the method adopted to construct the dataset, how the technologies covered were selected and how the relevant patents in the PATSTAT database were identified. Section 4 presents evidence on invention activity. Trends in water supply- and efficiency-related inventions worldwide are presented, and the main inventor countries are identified. Section 5 examines the main markets for water supply- and efficiencyrelated technologies. In section 6 data on international technology diffusion are presented. Section 7 discusses the findings and concludes.

2. Patents as indicators of invention and technology diffusion

There are a number of ways to measure technological innovation. Public and private research and development (R&D) expenditures or the number of scientific personnel in different sectors are the most commonly used measures (see OECD, 2014). Although such indicators reflect important elements of the innovation system, they have a number of disadvantages. For example, data on private R&D expenditures are generally only available for large companies and it is not possible to disaggregate them by technology or product line. Moreover, and more importantly, these data measure inputs to the invention process.

Patent data have several advantages over R&D expenditures and numbers of scientific personnel. First, patent data focus on outputs of the invention process (Griliches 1990) and provide a wealth of information on both the nature of the invention and the applicant. More importantly, patent data can be disaggregated into specific technological areas. Finally, patent data provide information about not only the countries where these new technologies are developed but also where they are used. It is these unique features of patent data that make our study possible.

2.1 The patent system

Before describing the indicators used in this and other studies, it is useful to briefly review how the patent system works. A patent is a legal title protecting an invention. To be patented, a product or process must be new, involve an inventive step and be susceptible of industrial application). Patents grant their owner a set of rights of exclusivity over an invention. The legal protection conferred by a patent gives its owner the *right* to exclude others from making, using, selling, offering for sale or importing the patented *invention* for the *term of the patent*, which is usually 20 years from the filing date, and in the country or countries where the patent has been filed (and subsequently granted). This set of rights provides the patentee with a competitive advantage. The cost of filing a patent for the inventor is the mandatory public disclosure of the description of the technology, which makes imitation easier and facilitates future technological developments.

To make things clearer, consider a simplified invention process. In the first stage, an inventor from a particular country discovers a new technology. She then decides where to market this invention and how to protect the intellectual property associated with it. A patent in country i grants her an exclusive right to commercially exploit the invention in that country. Accordingly, she will patent her invention in country i if she plans to market it there. The set of patents related to the same invention is called a patent family. The vast majority of patent families include only one patent (often in the home country of the inventor, particularly for large countries such as the US). When a patent is filed in several countries, the first filing date worldwide is called the priority date. Accordingly, the first patent is called the priority application and the first patent office is referred to as the priority office.

In this study, patents are sorted by priority year. We use the number of patent families as an indicator of the number of inventions. The number of technologies invented in country A and patented in country B is used as an indicator of the number of inventions transferred from country A to country B. This approach has been used extensively in recent years, particularly in the environmental field (Lanjouw and Mody, 1996; Eaton and Kortum, 1999; Dechezleprêtre et al., 2011; Dechezleprêtre et al., 2013).

2.2 The limitations of patent data

Studies using patent data have usually relied on patent data from OECD countries, especially the United States. For example, Popp (2006) uses patent data from Japan, the United States, and Germany to examine the invention and diffusion of air pollution control devices for coal-fired power plants. Johnstone et al. (2010) analyse the effects of policy and market factors on the development of renewable energy technologies in OECD member countries.

Despite the recent profusion of studies that have used patent data, patent-based indicators are imperfect proxies for technological invention and technology transfer and have several limitations (see OECD, 2009, for a recent overview). First, patents are only one of the means of protecting inventions, along with lead time, industrial secrecy, or purposefully complex specifications (Cohen et al. 2000; Frietsch and Schmoch 2006). In particular, some inventors may prefer secrecy to prevent public disclosure of the invention imposed by patent law or to save the significant fees attached to patent filing. However, there are very few examples of economically significant inventions that have not been patented (Dernis et al., 2001).

Second, the propensity to patent differs between sectors, depending on the nature of the technology (Cohen, Nelson, and Walsh 2000). It also depends on the risk of imitation in a country. Accordingly, inventions are more likely to be patented in countries with technological capabilities and a strict enforcement of IPR. This means that greater patenting activity could reflect either greater inventive activity or a greater propensity to file patents. Some methods used in this paper and described below allow us to partly control for this problem.

Another limitation is that while a patent grants the exclusive right to use a technology in a given country, it does not mean that the patent owner will actually exercise this right. This could significantly bias the results if applying for patent protection was free, as this might encourage inventors to patent widely and indiscriminately. However, patenting is costly—in terms of both the costs of preparing the application and the administrative costs and fees associated with the approval procedure. In the early 2000s, filing a patent cost around €5,000 in Japan, €10,000 in the US and €30,000 at the European Patent Office (EPO) (Roland Berger 2005). In addition, possessing a patent in a country may not be in the inventor's interest if that country's enforcement of intellectual property is weak, since publication of the patent can increase the risk of imitation (see Eaton and Kortum 1996, 1999). Finally, patent infringement litigation usually takes place in the country where the technology is commercialized (as this is where the alleged infringement occurs). Thus, inventors are unlikely to be willing to incur the cost of patent protection in a country unless they expect there to be a market for the technology concerned.

However, the fact remains that the value of individual patents is heterogeneous. Moreover, because many patents have very low value, the distribution is skewed, and as a consequence, the absolute number of patents does not perfectly reflect the value of technological innovation. Methods have been developed to address this issue and we implement them in this paper. In particular, in addition to presenting data on the number of inventions, we use data on international patent families to construct statistics for 'high-value inventions'. We use patents filed in at least two jurisdictions (so-called claimed priorities) to screen out low-value patents, as has been used elsewhere (Dechezleprêtre et al., 2011; Johnstone et al. 2012).[3]

3. Construction of the dataset

3.1 Technological scope

A number of technological options are available to expand the supply or improve the management of water resources. These options are widely categorized between supply-side options (that aim to increase water supply) and demand-side options (whose objective is to

[3] For a discussion of the merits of the use of "claimed priorities", as well as a review of a number of applications see Haščič and Migotto (2015).

reduce water consumption). To identify these options we surveyed the literature (Jury and Vaux, 2005; Jiménez Cisneros et al., 2014) and complemented this with information from interviews with experts working on water engineering.[4] The list of technologies covered in this paper, presented in Table 1, is the subset of potentially relevant technologies for which patents could be identified. Although we cover a wide range of water-related technologies, note that a number of technologies could not be included (such as water efficient domestic appliances) due to data constraints.

Table 1. Technologies covered in the study*

<table>
<tr><th>Supply-side</th><th>Demand-side</th></tr>
<tr><td>

Water collection

Underground water collection
Surface water collection (ie rivers, lakes)
Rainwater collection

Water storage (water tanks)
Desalination

</td><td>

Households

Domestic water efficiency (self-closing valves, aeration of water)
Sanitation (dual-flush toilets, dry toilets, closed-circuit toilets)
Greywater use

Distribution

Piping – reducing leakage & leakage monitoring

Manufacturing

Water efficiency in power production (water recycling, prevention of leakage)

Agriculture

Control of irrigation water application
Drought-resistant crops
Drip irrigation

</td></tr>
</table>

[4] We are especially indebted to Professor Nigel Graham (Head, Environmental and Water Resource Engineering Section, Department of Civil and Environmental Engineering, Imperial College London) for extremely helpful discussions.

***** Based on water-related technologies with implications for water supply and efficiency which are identifiable in the PATSTAT database - see Annex 1 for detailed explanation of technologies.

3.2 Patent search strategies

In order to identify patent documents in water supply and water efficiency technologies, the International Patent Classification (IPC) and the European Patent Classification (ECLA) have been used. These classifications are both available in the PATSTAT database and are searchable through online search engines. The very granular level of disaggregation (70,000 subdivisions for the IPC and 250,000 for the ECLA), makes it possible to identify specific technologies. The classifications were searched for a list of keyword related to all potentially relevant technologies. Previous work by the OECD has been used as the basis for the searches.[5] The list of patent codes used in this study and more detailed explanation of the technologies is shown in Annex 1.[6]

Two types of error may arise when building this type of dataset: Irrelevant patents may be included or relevant ones left out. The first error occurs if a selected IPC code covers patents that are not related to water supply or water efficiency. In order to avoid this problem, we carefully examined a sample of patent titles for every IPC code considered for inclusion in the dataset and excluded those codes that contain patents not related to water. As a consequence a few technologies could not be included in this paper because no IPC or ECLA patent classification code could be associated with them or the relevant codes were too broad to identify documents of specific relevance. This is the case for example of water-saving technologies for domestic appliances (washing machines and dishwashers).

[5] In particular: OECD (2011a) and OECD (2012a).

[6] Note that since the searches were undertaken the ECLA scheme has been superseded by the Cooperative Patent Classification (CPC) scheme. The ECLA symbols can be easily translated into the CPC using the available correspondence tables.

The second potential error—exclusion of relevant inventions—is less problematic. We can reasonably assume that all invention in a given field follows a similar trend. Hence, at the worst, our dataset can be seen as being a good proxy of innovative activity in the technology fields considered. However, because of the conservative approach we adopted when constructing the data, overall innovative activity may be underestimated, and the datasets in each technology field are unlikely to be equally exhaustive. Therefore, estimates of the absolute volume of inventive activity may be less reliable than estimated differences in temporal trends.

Importantly, the PATSTAT database includes data from all major patent offices in the world. Almost all of the patent offices not covered in the database are least developed countries where patents filings are seldom because enforcement of intellectual property rights is lacking. As a consequence, our data covers the near population of patents in the patent categories covered in the studies.

3.3 Construction of patent statistics[7]

In order to measure inventive activity, counts of patent families by year of application (priority date) are constructed. The PATSTAT database includes the country of residence of the inventors of those technologies for which patent protection is sought (independent of the country in which the applications are actually filed). Counting patent families rather than individual patent applications ensures that inventions are not double-counted, since a single invention may be

[7] See "Methodological Issues in the Development of Indicators of Innovation and Transfer in Environmental Technologies" in OECD (2011a)

patented in several countries[8]. This information is used to measure a country's invention performance.[9]

Patent applications filed in offices subsequent to the application filed at the first ("priority") office are referred to as duplicate applications. As a measure of technology diffusion, the count of the number of patent applications in recipient countries for technologies invented abroad is used (for example, the number of inventions developed in Germany and patented in China in 2005).

4. Inventive activity

4.1 Inventions by technological field

Between 1990 and 2010, over 28,000 inventions[10] were patented worldwide in water availability related technologies (see Table 2). This represents less than 0.2% of all inventions patented worldwide during this period of time. Of these inventions, around 8,500 can be considered to be of high value (i.e. they were patented in more than a single jurisdiction). Water patents represent 0.22% of all high-value inventions patented between 1990 and 2010, suggesting that water-related inventions are of slightly higher value than the average patented technology. Water availability related patents are about equally distributed among demand-side and supply-

[8] However the vast majority of patent families include only one country (often the home country of the inventor, particularly for large countries).

[9] Patents with multiple inventors are counted fractionally. For example, if two inventor countries are involved in an invention, then each country is counted as one half.

[10] These 28000 inventions subsequently led to around 50000 patents, some inventions being filed in multiple countries. See next section.

side technologies. Between 1990 and 2010, about 15,000 inventions were patented in demand-side technologies and over 13,000 in supply-side technologies.

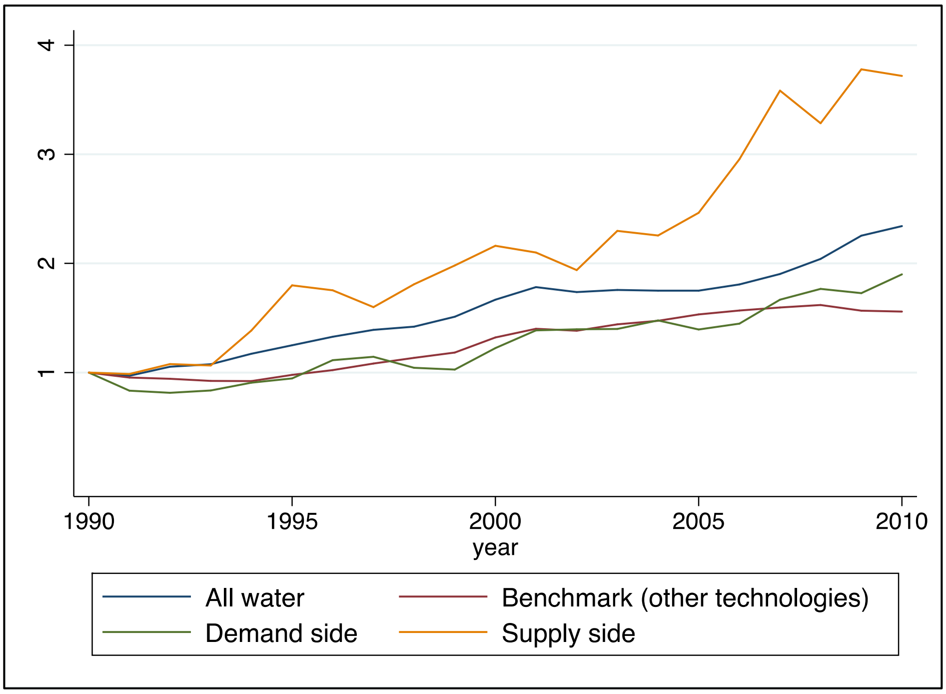
Table 2. Inventions in water-related adaptation technologies

Category	All inventions		'High-value' inventions	
	Number of inventions	Share of world's inventions	Number of inventions	Share of world's inventions
All water	28443	0.18%	8478	0.22%
Demand side	15048	0.09%	5717	0.15%
Supply side	13513	0.08%	2804	0.07%

On the supply side, the most important technologies in terms of the number of inventions patented is desalination with 4,500 inventions, followed by water storage and surface collection (i.e., lakes and rivers). Underground collection (pumping) and rainwater collection each saw about 2,000 inventions over 20 years. On the demand side, the most important technology by far is water efficiency in the power sector, with nearly 50% of all inventions. Other significant groups include domestic water efficiency (water aeration, self-closing taps…) and drip irrigation (see Figure 1 in Appendix for details).

The evolution of inventive activity in water-related adaptation technologies is displayed in Figure 1. The number of inventions developed annually has increased steadily over the 21-year period at an average annual growth rate of 4.5%. Demand-side and supply side technologies have grown in parallel. To put these trends in perspective, the trend of invention in water technologies is presented alongside the trend of invention activity for *all* patented technologies recorded in the database. The latter is labelled as the "benchmark". Given differences in scale, and in order to make the trends visually comparable, invention activity is normalised to equal 1 in 1990 for all sectors. Innovation activity in water-related adaptation technologies has grown at a slightly higher pace than innovation in other fields. Figure 1 also reveals that supply-side innovation has grown much faster than demand-side innovation: the number of annual supply-side inventions has increased almost fourfold in 20 years, while the number of annual demand-side inventions has less than doubled. Differences in underlying characteristics of water demand vs water supply management might explain the contrasted performance regarding patenting of technological inventions. For example, reliance on technological solutions in achieving efficiency improvements, importance of inventions originating in other sectors (e.g. ICT and smart water infrastructure), and differences in market structure and hence propensity to patent between supply-side and demand-side activities might help explain the observed differences in patenting trends.

Figure 1. Trend of inventive activity compared with benchmark (all patents filed worldwide)



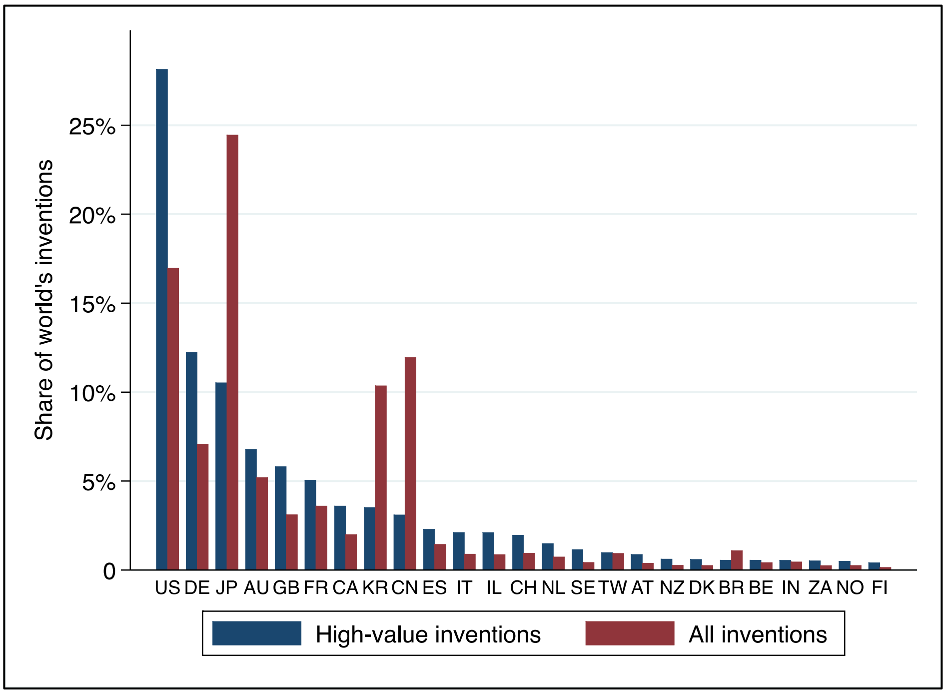
When we look at individual technologies, two technologies stand out on the demand side. Drought-resistant crops experienced a very high growth at the end of the 1990s and the beginning of the 2000s, before flattening towards the end of the period. Invention of greywater reuse technologies has taken off only recently. Other technologies have grown at a small and regular pace. On the supply side, the growth rate of invention activity appears remarkably similar in the five technologies analysed. The Figures are available in the online supplementary material.

4.2 Main inventor countries

Where does invention take place? Figure 2 shows the top 25 inventor countries in terms of both high-value inventions (i.e. those that are patented in at least two countries) and total water-related inventions for the years 2000-2010. We focus on the most recent part of our sample period, which we feel may be more interesting to the readers.[11] Since the number of inventions varies greatly across technological fields, the numbers reflected in Figure 2 are calculated as the average share of inventions across the 13 technologies in our data set. This means that the numbers are not driven by the largest technologies in the dataset, such as desalination or water-efficiency in electricity production.

[11] Following Lichtenberg and van Pottelsberghe de la Potterie (2001), we use an 11-year time period in order to mitigate the effect of annual fluctuations.

Figure 2. Top inventor countries in water-related adaptation technologies, 2000-2010



Note: we use 2-digit country codes from the European Patent Office. US=United States; DE=Germany; JP=Japan; AU=Australia; GB=United Kingdom; FR=France; CA=Canada; KR=Korea; CN=China; ES=Spain; IT=Italy; IL=Israel; CH=Switzerland; NL=Netherlands; SE=Sweden; TW=Taiwan; AT=Austria; NZ=New Zealand; DK=Denmark; BR=Brazil; BE=Belgium; IN=India; ZA=South Africa; NO=Norway; FI=Finland.

While the shares differ between the two measures, the only countries for which the rankings are very different are the main Asian inventor countries (China, Japan, Korea) for which there are a large number of 'low-value' (i.e. single country) patents. Germany, the United Kingdom and the United States have relatively more high-value inventions.

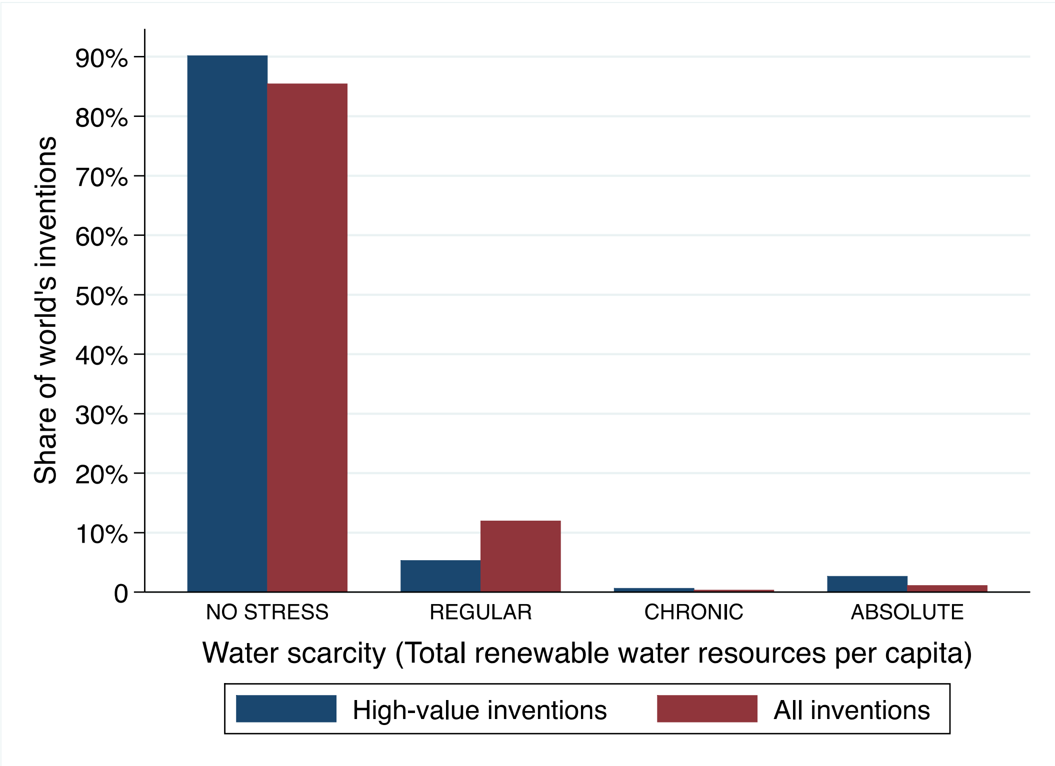
Patented invention is highly concentrated amongst a few countries. The top ten countries account for nearly 80 percent of all high-value inventions developed between 2000 and 2010. The United States, Germany and Japan are the three top inventor countries on average for water-related technologies. Four emerging economies (China, Brazil, India and South Africa) are among the world's top 25 countries, but no less-developed country figures in the list (see details in Annex 2).

Importantly, water-related invention is rarely observed in the data in countries with severe water stress issues. In Figure 3, we group countries according to Falkenmark's (1989) indicator of national water scarcity, measured as total renewable water resources per capita (m^3/inhab)[12]. We find that between 80-90% of invention worldwide happens in countries with low or moderate water scarcity. We interpret this national indicator with caution, noting its failure to capture the complex spatial and temporal patterns of sub-national water availability and demand (Rijsbersman, 2006; Mason, 2013)[13]. In addition to physical scarcity, economic scarcity, associated with limited investment in water, or institutional capacity to satisfy the demand for water (Seckler et al., 1998), is also likely to influence invention and diffusion of technologies. But while this result is certainly a reflection of the fact that most developed economies do not suffer severe water stress (although sub-national differences exist), it is still striking and highlights the importance of international technology transfer and of policies that facilitate broad diffusion of these technologies in water-stressed countries.

[12] The threshold values of water scarcity are the following: absolute if renewable water resources are <500 m^3 per capita, chronic if renewable water resources are between 500 and 1000 m^3 per capita, regular between 1000 and 1700 m^3 per capita, and no stress above 1700m^3.

[13] Similar results to those in Figure 3 were obtained using the ratio between total water withdrawal over total renewable water resources (thus capturing a better measure of the balance between supply and demand than Falkenmark's index).

Figure 3. Water scarcity and share of world's inventions in water-related adaptation technologies, 2000-2010



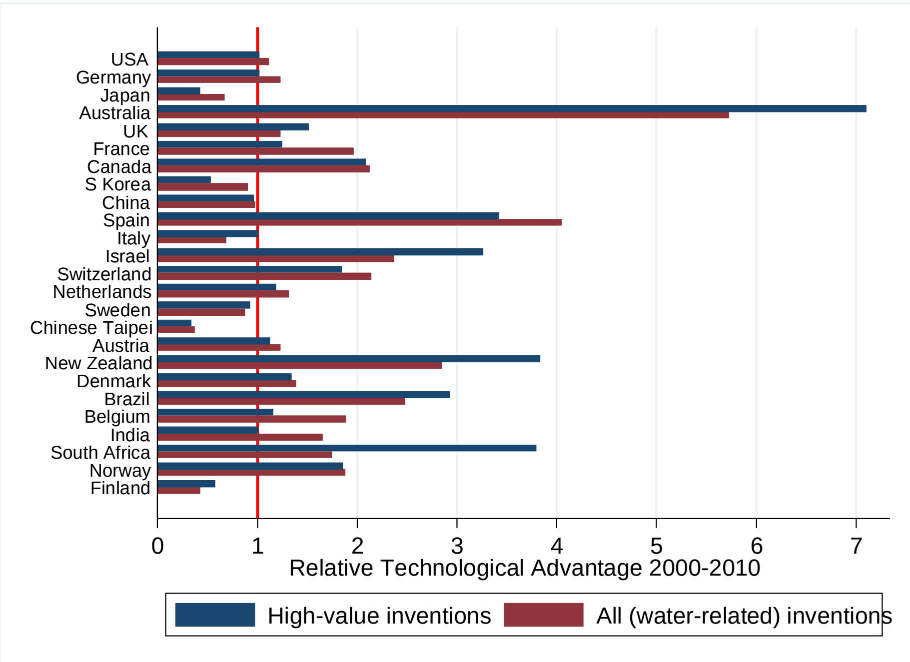
Note: indicator of water scarcity based on Falkenmark (1989)

When we look at individual technologies, the United States, Germany and Japan appear as the main inventor countries in many technologies. However, some countries have strong positions in specific fields (Table A2 in the online supplementary materials presents the top three technologies for the main OECD and BRICS inventor countries). For example, given their usual place in the hierarchy of worldwide invention the cases of Australia (top inventor globally for greywater, and rainwater collection and third for water storage) and Israel (second largest inventor in drip irrigation and in the top 10 for control of watering and desalination) are striking and reflect both countries' high physical and low economic water scarcity and relatively high levels of irrigation. China, the world's second largest irrigator by area after India, is the third most innovative country in drought-resistant crops, and sixth for drip irrigation. China is implementing inter-sectoral re-allocation of water away from agriculture, and water withdrawals per hectare of irrigated land declined by 20% and for agriculture per person by 13% between 1990 and 2012 (Doczi et al., 2014). Noticeably, Malaysia appears in the top 20 inventor countries for greywater use, as does Indonesia for surface water collection. However, Singapore which is noted for its innovation in water management and technology, is absent. Tables presenting data on the top 20 inventor countries in each technology are available in the Online Supplementary Material.

In order to further investigate the specialization of countries in water-related technologies, each country's share of inventions in such technologies is divided by their share of inventions in all technologies (see Figure 4). For example, the US share of worldwide inventions in all technologies is 27.4% while the figure for water-efficiency technologies is 28.1%, so the US Relative Technological Advantage (RTA) is 1.03 (28.1/27.4). In other words, the water-related invention effort in the US mirrors its overall innovative performance. Conversely, some other countries appear to be highly specialized in water-related adaptation technologies: Australia (RTA=7), New Zealand, South Africa, Spain, Israel and Brazil. While Australia, Spain and Israel are countries where water resources are scarce, the specialization of Brazil is more surprising and may be explained by the presence of desert areas in Brazil, which create local water scarcity issues. For the Asian countries the specialization patterns previously observed remain. In particular, Japan, China and Korea appear not to be particularly specialized in water technologies.

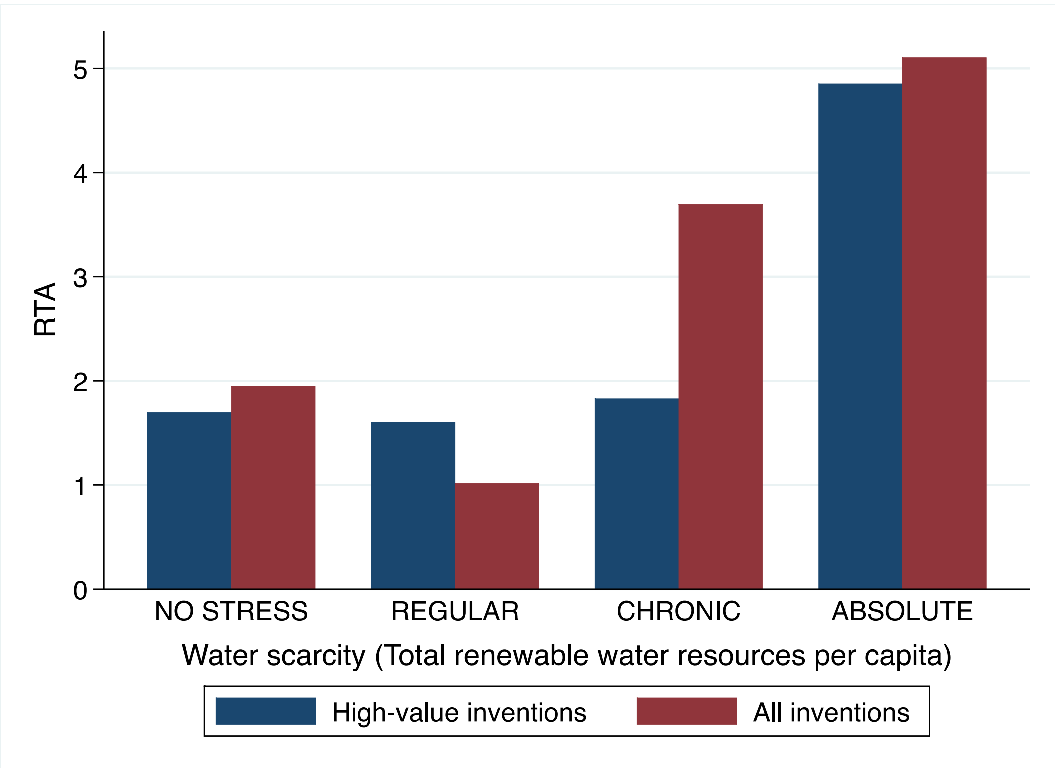
Interestingly, countries' relative position in global invention efforts varies significantly over time. For example, Brazil, South Africa and India have strongly increased their efforts toward water inventions between the period 1990-2000 and 2000-2010, while the relative position of China and Israel has deteriorated (see Figure A3 in the online supplementary material).

Figure 4. Relative invention of water to all technologies (Relative Technological Advantage) 2000-2010



More generally, is there a link between water scarcity and countries' specialization in water invention? In Figure 5 countries are grouped according to the water scarcity index used in Figure 3 and the average Relative Technological Advantage is calculated for the same groups. Figure 5 indicates a positive correlation between specialization in water invention and water scarcity, suggesting that countries with important water scarcity issues – irrespective of their size and their overall invention capabilities – seem to specialize in water efficiency technologies, even if, as shown by Figure 3, their contribution to global water invention efforts are low. This suggests that the development of local R&D capabilities could boost water-scarce countries' contribution to global innovation. It is interesting to note that the positive correlation is particularly visible when all inventions – included low-value patents filed in a single country – are considered. This reflects the fact that countries with chronic or absolute water scarcity issues are invariably developing countries, whose water technologies are primarily tailored for the local market.

Figure 5. Relative Technological Advantage and water scarcity



Note: indicator of water scarcity based on Falkenmark (1989)

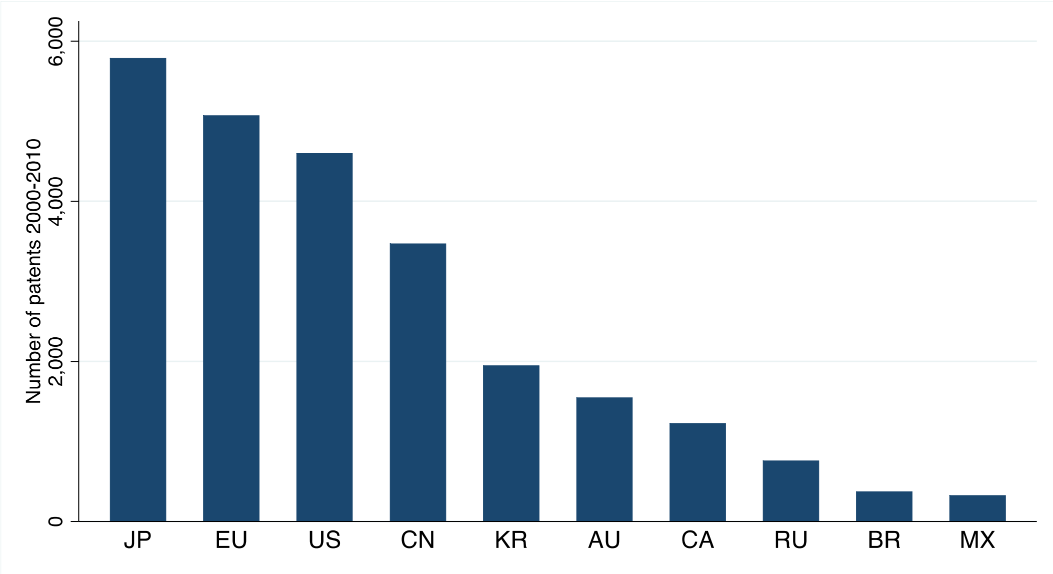
5. Technology markets

In Section 3 the countries in which new inventions are developed were identified. In this section data are presented on where these inventions are protected through the local intellectual property system (independently as to where there inventions were developed in the first place). As explained in Section 2, since patent protection is costly both in terms of financial costs and in terms of information revelation, this serves as a proxy for the existence (or at least expectation of the existence) of a market for the protected technologies.

Where have water technologies most commonly been patented? Figure 6 presents the number of patents filed between 2000 and 2010 in the major patent offices. Not surprisingly, Japan, Europe[14] and the US are the three main markets for water-related technologies. They are followed by China, Korea and Australia. Brazil and Mexico also belong to the top 10 patent offices. Unbundling the European data into applications at national patent offices Germany, UK and France are the top three inventors. However, Spain enjoys an unusually high position, suggesting this country is an important market for water-efficiency technologies in Europe.

[14] A patent is considered European if it is filed in any European country *or* at the European Patent Office.

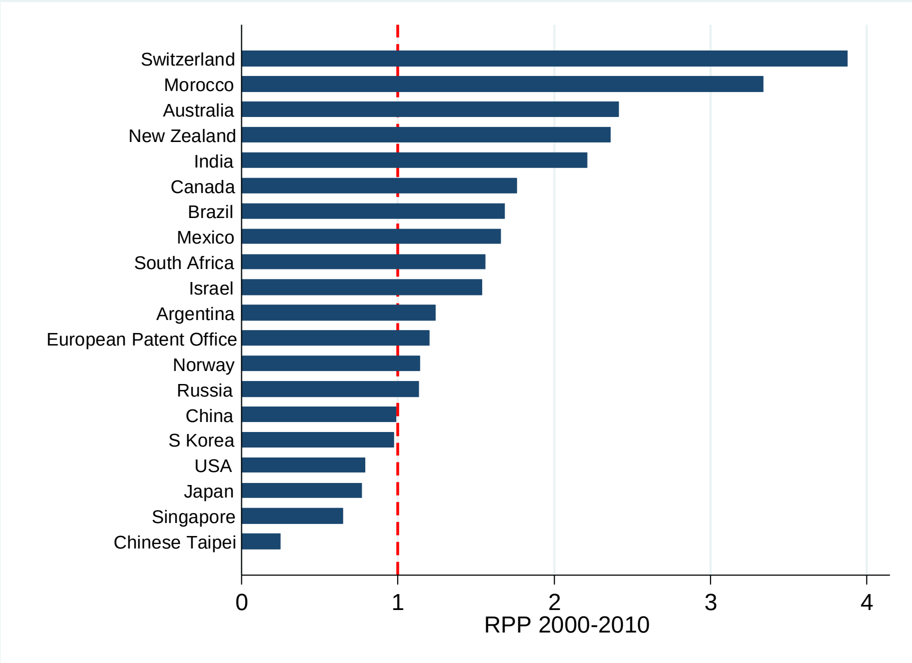
Figure 6. Number of Patents Protected at Main IP Offices



Note: "EU" denotes patents filed either at the EPO (regional office) or at any national patent office in Europe.

How important is the market for water-related adaptation technologies in the countries over which each patent office has jurisdiction? In Figure 7 a specialization index is presented. This is calculated as the ratio between the share of patents in each office and the global share of patents in the field, referred to as the Relative Propensity to Patent (RPP). A value greater than one indicates that a country is an important market for water technologies relative to other technologies. Interestingly, the most water-stressed countries are not always the countries where water technologies are most heavily patented. While Australia, Morocco and Israel are – unsurprisingly – significant markets for water technologies, so are Switzerland, Canada and Brazil, which have large per capita water resources. This suggests that other factors, such as social and cultural specificities and local water conservation policies may play a role in driving the diffusion of water-saving technologies. Disaggregating the data by technology, Switzerland receives a relatively high number of patents in surface water collection and energy efficiency in power production. Brazil and Canada are important recipient countries for drought-resistant crops, control of watering and domestic water efficiency. Many greywater patents are being filed at the Canadian patent office.

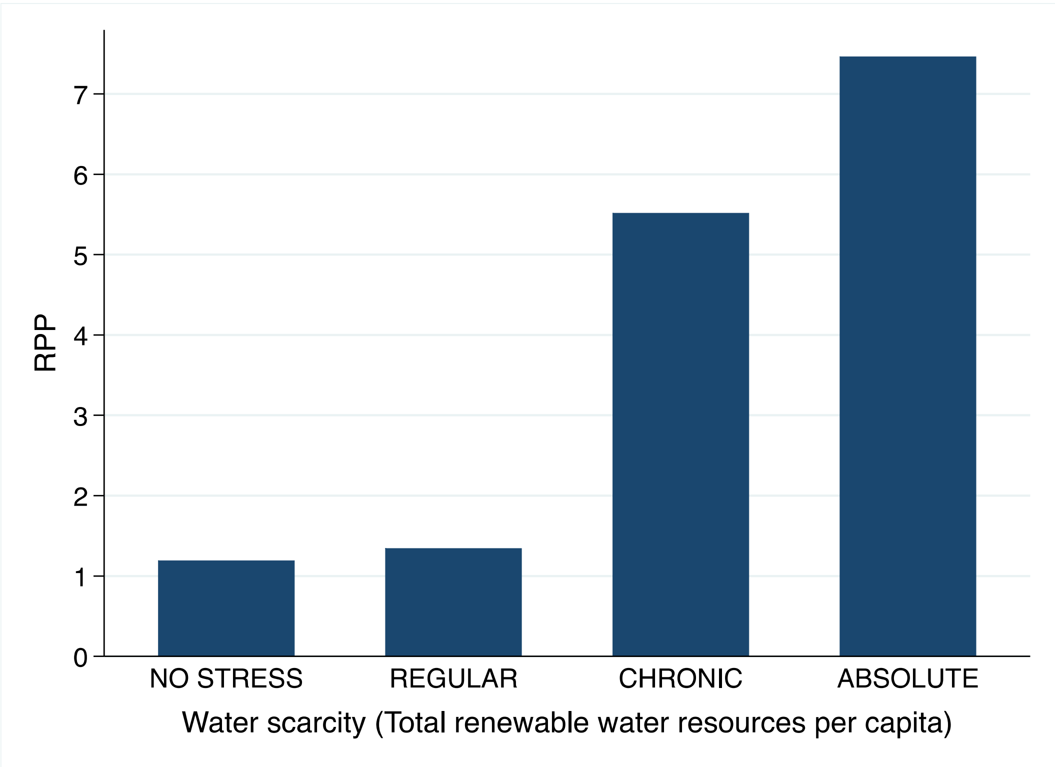
Figure 7. Relative preponderance of water-related adaptation patents by office



This specialization may be the result of foreign inventors responding to local demand conditions. Adjusting for this possibility by focussing only on "local" inventors, the numbers change only slightly. Europe appears to be less specialized using this measure, suggesting that European inventors are developing many water technologies to serve foreign markets. However, we find that countries such as Canada, Brazil and Switzerland are still specialized in water technologies using this measure.

Do water-stressed regions receive particularly high volumes of water-related patents? Figure 8 presents the relative propensity to patent across country groupings based on their water vulnerability index. We find that independent of their size or their general propensity to use patents, countries with severe water scarcity issues tend to receive relatively more patents in water-efficiency technologies. This suggests that there exists a stronger local demand for water-saving technologies in these countries, and that inventors worldwide react to this perceived profit potential by filing more water patents.

Figure 8. Relative preponderance of water-related patents and water scarcity



What has been the recent evolution of patenting activity at the various IP offices? When looking at the growth of patent applications between the period 1990-2000 and 2000-2010, the highest growth rates of patent applications can be found in fast-growing economies, including China, Mexico and South Korea. South Korea stands out as the country in which the market for water-related technologies has grown the most during the last 10 years, both in absolute terms and relative to other technologies. South Africa, India, Mexico and Australia are other markets where water technologies represent an increasing share of patent filings (see Table A4 in the online supplementary material).

What may be more surprising, though, is that in countries with no significant water scarcity issues such as Switzerland or Norway the market for water technologies also grew a lot. Several factors might be at play. For example, it may reflect the stringency of policies aimed at reducing water use, such as the Federal Law on the Protection of Water adopted by Switzerland in 1991, which resulted in a decrease in water use in Switzerland (including industrial, commerce and agricultural use) from over 500 litres per person per day in 1981 to around 350 litres today, despite the fact that the country has large water resources, with an estimated six percent of Europe’s total freshwater stock (but only 1% of the population). Yet other explanations are possible, especially given that Switzerland is the homeland of a number of industries active in the water sector (incl. food and beverage, pharmaceuticals and chemicals).

6. International technology diffusion

6.1 The internationalisation of patent filings

The 28,443 inventions developed between 1990 and 2010 in water-related adaptation technologies have resulted in 53,230 individual patent applications. This means that each invention has been filed in 1.87 patent offices on average (see Figure A5 in the online supplementary material). This is slightly more than the average for non-water technologies (1.63), suggesting that water technologies might have wider application and/or be of higher value than the average technology. Over the period 1990-2010 water-related technologies have consistently been protected in more patent offices than the average technology, and the gap has been increasing during the 2000s. The average family size has grown from about 1.6 patent offices in 1990 to around 2 offices in 2008. This increase has concerned both demand-side and supply-side technologies.

However, significant variation is found between technologies in their average geographic extension. Technologies on the demand-side are filed in 2.16 countries on average, while technologies on the supply-side are only protected in 1.55 countries. Drought-resistant crops are protected in almost four patent offices (with a peak at 6 at the end of the 1990s). Greywater use has also experienced a recent surge in geographical coverage, although to a lesser extent. The international extension of most other demand-side technologies has remained flat across time. As for supply side technologies, markets have recently expanded for surface water collection and underground collection. This reflects different patenting strategies: for example, drought-resistant crops patent applications are mainly filed by large companies, such as BASF, Monsanto and Bayer, who have access to global markets and can afford multiple filings (see also Agrawala et al., 2012). Interestingly, the market for desalination inventions appears remarkably stable across time, although innovative activity in this field is growing, particularly due to growth of patents filed only in China (see section 3).

6.2. Cross-border patent transfers

Proxy data on international technology transfer, as reflected in cross-border patenting is now presented. This is defined as patent applications filed by an inventor residing in a country that is different from the one in which protection is sought (e.g., a patent filed in the United States by an inventor working in Germany[15]). Using patents to measure technology transfer has been used increasingly in recent years (Dechezleprêtre et al., 2011; Dechezleprêtre et al., 2013; Haščič and Johnstone 2011; Johnstone and Haščič 2011) following early works by Eaton and Kortum (1996, 1999) and Lanjouw and Mody (1996).[16]

The proportion of patents filed by inventors residing in a country which differs from the office of protection between 1990 and 2008[17] has been consistently higher for water-related adaptation technologies than for the average patented technology (see Figure A9 in the online supplementary material). However, there are important differences between supply-side and demand-side technologies. Demand-side technologies are significantly more likely to be transferred abroad than supply-side technologies. A possible explanation for this result is that supply-side technologies are more tailored to local conditions, restricting international market opportunities. Another explanation could be that demand-side and supply-side technologies target two separate markets, with different market structures, and this can explain the different performance regarding patenting. Typically, demand-side technologies target markets for buildings equipment and consumer products, and this may explain why such inventions tend to be patented in a larger number of countries (see also Section 4.1 above).

[15] We use information on the inventor's country of residence, irrespective of his nationality, to determine where inventions are developed.

[16] For a methodological discussion see Annex A in OECD (2011a).

[17] Note that in this case we use a cut-off data of 2008 since there is a lag of between 18 and 36 months in which 'duplicate' filings can be posted.

What are the origins and destinations of these transfers? Table 3 presents the distribution of water-related technology flows between OECD countries, emerging economies[18] and other countries from 2000 to 2010. Over these years, nearly 15,000 patented inventions sought protection abroad. Not surprisingly, technology is exchanged mostly between OECD countries (79 percent of all transfers), while transfers between developing countries are almost non-existent (less than 1 percent of total transfers). Transfers from OECD countries to emerging economies are much more frequent than transfers from emerging economies to OECD countries. Importantly, technology flows from OECD to emerging countries are significantly less frequent for water-related technologies than for other technologies (see Table A5 in the online supplementary material).

Table 3. International transfers of water-related adaptation technologies

Origin \ Destination	OECD	Emerging	Other
OECD	11634 (78.83%)	1731 (11.73%)	375 (2.54%)
Emerging	593 (4.02%)	35 (0.24%)	19 (0.13%)
Other	269 (1.82%)	57 (0.38%)	48 (0.32%)

[18] Emerging countries include Argentina, Brazil, China, Colombia, Egypt, Indonesia, India, Morocco, Malaysia, Peru, Philippines, Pakistan, Thailand, Chinese Taipei and South Africa

6.3 International collaboration in technology development

Since patent applications include information on the country of residence of all inventors having worked on the invention, patent data can be used to investigate cross-border collaboration in technology development (see Haščič et al. 2012 for an example of possible applications of this measure). We find that 10% of water-related patents have been developed by inventors from at least two different countries. This rate of international co-invention is identical for non-water technologies. However, we find important discrepancies between technologies. Over 14% of demand-side technologies are co-invented, compared to only 5% for supply-side technologies. Interestingly, more than half of inventions in drought-resistant crops involve international

Which countries are most likely to collaborate with each other? Not surprisingly, as shown in Table 4, two out of three joint inventions in water technologies are developed by inventors from two or more OECD countries. One other result stands out. When comparing co-invention in water technologies with co-invention in other technologies, we find that inventors from OECD countries are significantly less likely to collaborate with inventors from emerging economies relative to the general rate of collaboration for all technologies. We also find than inventors from emerging economies are somewhat less likely to collaborate in the area of water invention with inventors from other emerging economies relative to other fields.

Table 4. International co-inventions by country grouping

Collaborating	Water technologies	Other technologies

countries		(benchmark)
OECD-OECD	873 (73.24%)	67.62%
Emerging-Emerging	6 (0.50%)	4.20%
Other-Other	12 (1.01%)	0.80%
OECD-Emerging	178 (14.93%)	18.18%
OECD-Other	106 (8.89%)	7.58%
Emerging -Other	17 (1.43%)	1.63%

The proportion of internationally co-invented patents by inventor country for water-related adaptation technologies varies across countries. For example around half of water inventions are developed through international collaborations in Switzerland and in Spain, while in Japan the proportion is only 6%. Among emerging economies, Indian inventors coinvent nearly 75% of their water inventions with inventors from other countries. On the other hand, Brazil and China have a much lower rate of international co-invention (see Table A8 in Appendix).

High rates of collaboration are observed between Germany and Switzerland, US and Israel, US and Turkey, US and Belgium, Germany and UK. Not surprisingly, the US has been involved in 17 of the 25 most productive technology development relationships between 2000 and 2010. Interestingly, however, US inventors collaborate not only with inventors from other rich countries, such as Canada, but also with inventors from developing countries, most notably India, with which our data indicates that 54 inventions were jointly developed, and Pakistan (see Table A9 in Appendix).

6.4 International knowledge flows

In order to analyse international knowledge flows, we use data on patent citations. Patent documents offer a paper trail of knowledge flows, as inventors are required to reference previous patents that have been used to develop the new technology described in the patent. It is therefore not surprising that patent data have been widely used in empirical studies of knowledge spillovers[19] (see, for example, Jaffe, Fogarty and Bank, 1998; Trajtenberg, 1990; Cabellero and Jaffe, 1993; Jaffe and Trajtenberg, 1996 and 1998). Since we are mostly interested in international flows of knowledge we focus on cross-border citations – for example, a citation made by an inventor working in Germany to a patent developed in Japan.

The distribution of knowledge flows as evidenced by patent citations is even less evenly distributed than the distribution of technology flows. Over 93% of cross-border flows of knowledge in water technologies happen between OECD countries. The predominance of knowledge diffusion between developed countries is not specific to water technologies, but significantly more knowledge seems to be flowing from OECD countries to less developed countries. Knowledge flows between less developed countries are also significantly larger, and perhaps even more interestingly, knowledge flows from less developed countries to OECD

[19] The limitations of patent data have been discussed at length in the literature and are now well understood (see OECD 2009 for a review). Since not all inventions are patented (Trajtenberg, 2001), patent citations underestimate the actual extent of knowledge spillovers, but are considered as a good indicator of knowledge flows. An important issue is that some citations do not represent true knowledge flows, in particular self-citations (citations made to a patent by the same inventor) and citations added by the patent examiner. However, our data allows us to identify both self-citations and citations added by patent examiners, and to focus on citations that most probably correspond to true flows of knowledge.

countries also seem to be particularly important, suggesting water efficiency is a domain where the North is learning from the South.

Focusing on knowledge flows arising from documents from inventors/authors in emerging economies we see interesting differences. For example, Brazilian and Indian documents are much more likely to be cited in North America than is the case for the other emerging economies. Chinese documents are much more likely to be cited in Europe. South African documents have a higher percentage of citations in Australia (see Figure A11 in Appendix).

7. Conclusions and discussion

We conclude with a summary of our findings and discussions of policy options for accelerating the transfer of water technologies to developing countries and directions for future research.

7.1 Summary of findings

In this paper, the first descriptive analysis of invention activity in water supply- and efficiency-related technologies is presented. Our analysis is based on a unique data set comprising over 50,000 patents filed in 83 patent offices between 1990 and 2010. The analysis covers technologies aimed at increasing the supply of water (e.g. desalination, water storage, pumping) and technologies whose objective is to reduce water consumption (domestic and industrial water efficiency, greywater use, drought-resistant crops, drip irrigation, etc). Three results stand out from our analysis:

- First, although invention activity in water-related technologies has been increasing over the last two decades, this growth has been disproportionately concentrated on supply-side technologies. This suggests that priority has so far been given to expanding water resources rather than reducing consumption by means of water-efficiency measures. Differences in underlying characteristics of water demand versus water supply management (market structure, propensity to patent, reliance on technological solutions) might help explain the observed differences in patenting trends. For example, water demand management creates a dilemma for water utilities as it relies on both consumer participation and, in situations of volume-based rate structures like the UK, it compels them to implement actions that result in loss in their own revenue (Speight, 2015). Nevertheless, the challenges posed by water scarcity in the face of a growing population and per capita consumption are unlikely to be solved solely by increasing water pumping and resorting to desalination, a highly energy-intensive technology. More invention on the demand-side is needed.

- Second, over 80% of inventions worldwide happen in countries with low or moderate water scarcity. While this is certainly a reflection of the fact that most developed economies which are at the technology frontier do not face severe water stress, it highlights the importance of international technology transfer and policies that facilitate broad diffusion of these technologies in water-stressed countries. However, some countries with chronic and absolute water scarcity issues, such as Australia, Spain and Israel, seem to be relatively specialized in water efficiency technologies.
- Third, although we observe a positive correlation between water scarcity and local filings of water patents, some countries with high water availability, in particular Switzerland and Norway, nevertheless appear as significant markets for water-efficiency

technologies, suggesting that drivers other than local demand, such as regulation and social and cultural factors, play a key role in explaining the global flows of technologies.

Some interesting results also emerge with respect to the degree of internationalisation of water supply and efficiency innovation: i) relative to technologies in general such technologies are more likely to be patented in multiple countries and this gap has been increasing, indicating their broad market applicability; ii) when comparing co-invention in water technologies with co-invention in other technologies, we find that inventors from OECD countries are significantly less likely to collaborate with inventors from emerging economies relative to the general rate of collaboration for all technologies; and, iii) while most cross-border flows of knowledge happen between OECD countries, knowledge flows from less developed countries to OECD countries are relatively important, suggesting water efficiency is a domain where the North is learning from the South.

7.2 Policies to accelerate invention and technology diffusion

How can inventive activity and international diffusion of water technologies be encouraged and accelerated? Empirical assessment of the impact of different policies and measures would require collecting commensurable data on water-related policies across countries, and this is complicated because water policies are often implemented at the local level. However, the more general literature on the economics of innovation and technology diffusion offers some interesting conceptual insights.

Economic theory suggests that market forces provide insufficient incentives for investment in the development or diffusion of water-efficiency technologies. Two principal market failures may explain this underinvestment.[20] The first market failure arises from the public good nature of water resources. When water can be used freely, consumers lack incentives to invest in the use of water-efficient technologies. Thus, without appropriate policy interventions, the market for technologies that reduce water consumption will be limited, reducing incentives to diffuse such technologies and hence to develop them in the first place. The second market failure is the public goods nature of knowledge (see, for example, Geroski 1995), which impedes technological change at the R&D stage. In most cases, new technologies must be made available to the public for the inventor to reap the rewards of invention. However, by making new inventions public, some (if not all) of the knowledge embodied in the invention becomes public knowledge. This public knowledge may lead to additional innovations, or even to copies of the current innovations.[21] These knowledge *spillovers* provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of research activity. Economists studying the returns to research consistently find that knowledge spillovers result in a wedge between private and social rates return to R&D (see for example Mansfield (1977, 1996), Pakes (1985), Jaffe (1986), Griliches (1992), Hall (1996), and Jones and Williams (1998).

Regulation is one obvious policy instrument that can be used to foster the creation of markets for water efficiency technologies and provide an incentive for firms to develop and acquire new technologies. Since historically industrialized countries have more advanced environmental and

[20] The literature has identified many other market failures and barriers that impede the development of environmental technologies. These include imperfections in the market for capital, lock-in and path dependency of previous investments due to long-lived capital, market power, network effects and dominant designs.

[21] Intellectual property rights, such as patents, are designed to protect inventors from such copies. However, their effectiveness varies depending on the ease in which inventors may “invent around” the patent by making minor modifications to an invention. See, for example, Levin *et al*. (1987).

climate regulations, it is not surprising that they have also developed more technologies and attracted more technology transfer. For climate change mitigation technologies, it has been established, for example, that higher fuel prices stimulate the development of electric and hybrid vehicles (Aghion et al., 2012) and that the introduction of the European Union Emissions Trading System led regulated firm to increase their invention efforts (Calel and Dechezleprêtre, 2014). Success in leakage mitigation highlights the potential for innovation spurred by regulatory requirements and funding availability; International Water Association water audit procedures have been adopted as a standard in many countries, drawing upon insights from regulator-driven UK water industry leakage reduction. The global leakage reduction and pipeline rehabilitation market is now estimated at around $3 to $5 billion (Speight, 2015).

General factors such as trade openness, the IPR system, and local innovation capabilities (e.g., human capital) also help explain why technology development and diffusion is concentrated in developed countries. Since technology transfers take place through market channels such as trade, FDI, or licenses, they occur more frequently in open economies (Saggi 2002; Hoekman, Maskus, and Saggi 2005). Lowering barriers to trade and FDI is thus a way to foster technology diffusion. Speight (2015) identifies strong leadership and investment from regulators as important drivers of innovation and highlights the example of innovation for water in Singapore. During the last 50 years Singapore has gone from a country with little centralized sanitation and reliance on imported water to an internationally renowned hub for research and development in water and wastewater treatment processes. [22]

[22] The focus on treatment partly explains Singapore's absence from the high patenting countries in our data.

Empirical evidence also suggests that effective patent protection is a means to promote technology transfer toward developing countries when foreign technology providers face the threat of imitation by local competitors (Maskus 2000; Smith 2001; Hoekman, Maskus, and Saggi 2005; Mancusi 2008; Parello 2008). Along the same lines, stronger patent protection encourages the use of FDI and licenses, which induces technology transfer that goes beyond the mere export of equipment or goods (Smith 2001).

Since the positive effect of IPR depends on the threat of local imitation, it mostly concerns those recipient countries that already have technology capabilities, such as emerging economies. The higher the level of domestic human capital, the higher the level of foreign technology transfer (Eaton and Kortum 1996), as well as local spillovers from trade and FDI (Borensztein, De Gregorio, and Lee 1998). By contrast, low absorptive capacities mean shortages of skilled technical personnel, a lack of information on available technologies, and high transaction costs (Worrell et al. 1997; Metz et al. 2000).

7.3 Directions for future research

An important area for future research would be to complement this descriptive study with econometric analyses that would help better understand the role of public policy and other drivers of inventive activity and of international diffusion of water technologies. An important limitation of our work is that our focus on patents fails to capture non-R&D innovation, and practical experience suggests that incremental innovation (technological and non-technological) is taking place (Wehn and Montalvo, 2014). It would thus be interesting to complement this study with analyses of unpatented innovation in order to get a more holistic vision of the water innovation landscape. This would help understand how invention in this field may best be encouraged. Coupling large sample analyses with finer-grained case study narratives will help disentangle the effects of market demand, water conservation policies, local R&D capabilities and social and environmental factors; a promising avenue for future research.

REFERENCES

IPCC Working Group II, “Climate Change 2014: Impacts, Adaptation and Vulnerability” (2014) http://ipcc-wg2.gov/AR5/

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and J. Van Reenen, 2012. “Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry”. Forthcoming, *Journal of Political Economy*

Agrawala, S., C. Bordier, V. Schreitter and V. Karplus, "Adaptation and innovation: An analysis of crop biotechnology patent data," OECD Environment Working Paper N° 40 (Paris: OECD Publishing, 2012).

Calel, R., and Dechezleprêtre, A., 2014. “Environmental Policy and Directed Technological Change: Evidence from the European carbon market”. Forthcoming, *Review of Economics and Statistics.*

Convery, F., (2013) “Reflections - shaping water policy: What does economics have to offer?”, *Review of Environmental Economics and Policy*, Vol. 7, No. 1: 156–174.

Dechezleprêtre, A., Glachant, M., and Ménière, Y., 2013. “What Drives the International Transfer of Climate Change Mitigation Technologies? Empirical Evidence from Patent Data”. *Environmental and Resource Economics (2013),* 54(2): 161 – 178.

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., and Ménière, Y. (2011) “Invention and transfer of climate change mitigation technologies on a global scale: A study drawing on patent data”, *Review of Environmental Economics and Policy*, Vol. 5, No. 1: 109-130.

European Innovation Partnership on Water (EIP Water) “*Barriers and bottlenecks for Innovation in the Water Sector.*” Final Report, including comments from the Steering Group. January 2014.

Falkenmark, M. (1989) “The massive water scarcity now threatening Africa: why isn't it being addressed?” *Ambio* 112-118.

Gleick, P. H. (2003). “Global freshwater resources: soft-path solutions for the 21st century.” *Science*, 302(5650): 1524-1528.

Gosling, S. N. & N. W. Arnell (2013) “A global assessment of the impact of climate change on water scarcity” *Climatic Change*, August.

Grafton, Q. et al. (2011) “An integrated assessment of water markets: A cross-country comparison”, *Review of Environmental Economics and Policy*, Vol. 5, No.2 (2011): 219-239.

Haščič, I. and M. Migotto (2015) "Measuring Environmental Innovation Using Patent Data" *OECD Environment Directorate Working Paper* (Paris: OECD Publishing, forthcoming).

Haščič, I. and N. Johnstone (2011), “The Clean Development Mechanism and international technology transfer: Empirical evidence on wind power”, *Climate Policy* Vol. 11, No. 6 (2011): 1303-1314.

Haščič, I., N. Johnstone and N. Kahrobaie (2012) "International Technology Agreements for Climate Change: Analysis Based on Co-invention Data." *OECD Environment Working Papers* No. 42 (Paris: OECD Publishing).

Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila (2014) Freshwater resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Johnstone, N., Haščič, I. and D. Popp (2010) "Renewable energy policies and technological innovation: Evidence based on patent counts", *Environmental and Resource Economics* 45(1): 133-155.

Johnstone, N., Haščič, I., Poirier, J., Hemar, M., and C. Michel (2012) "Environmental policy stringency and technological innovation: Evidence from survey data and patent counts", *Applied Economics* 44(17): 2157–2170.

Johnstone, Nick and Ivan Haščič (2011) "Environmental policy design and the fragmentation of international markets for innovation" in *Reforming Rules and Regulations: Laws, Institutions and Implementation,* ed. Ghosal, Vivek (Cambridge, Mass.: MIT Press, 2011) Chapter 4, Pages 79-103.

Jury, W. A., & Vaux, H. (2005). "The role of science in solving the world's emerging water problems." *PNAS*, 102(44), 15715-15720.

Keller, J., Keller, A., & Davids, G. (1998). "River basin development phases and implications of closure." *Journal of Applied Irrigation Science*, 33(2), 145-163.

Krozer, Y., Hophmayer-Tokich, S., van Meerendonk, H., Tijsma S., Vos, E (2011) "Innovations in the water chain – experiences in The Netherlands", *Journal of Cleaner Production* 18: 439–446

Lanjouw, J.O. and A. Mody (1996) "Innovation and the international diffusion of environmentally responsive technology", *Research Policy* 25: 549-571.

Mason, N. (2013) "Easy as 1, 2, 3? Political and technical considerations for designing water security indicators." In B.A. Lankford, K. Bakker, M. Zeitoun & D. Conway (eds.) *Water Security: Principles, Perspectives and Practices*. Pp 183-203. London: Earthscan Publications.

Mason, N. and Calow, R. (2014) "*The real water crisis: inequality in a fast changing world.*" Overseas Development Institute, London.

Molle, F., Wester, P., & Hirsch, P. (2010). "River basin closure: Processes, implications and responses." *Agricultural Water Management*, 97(4), 569-577.

OECD, “Policies to Support Eco-innovation in Israel”, Free document, Environment Directorate (Paris: OECD, 2011b). http://www.oecd.org/israel/48354947.pdf

OECD, *Better Policies to Support Eco-innovation* (Paris: OECD Publishing, 2011c).

OECD, *Energy and Climate Policy: Bending the Technological Trajectory* (Paris: OECD Publishing, 2012a).

OECD, *Improving Water Management: Recent OECD Experience*. (Paris: OECD, 2003).

OECD, *Invention and Transfer of Environmental Technologies* (Paris, OEC, 2011a).

OECD, *OECD Environmental Outlook to 2050: The Consequences of Inaction* (Paris: OECD Publishing, 2012b)

OECD, *Patent Statistics Manual* (Paris: OECD, 2009).

OECD, *Pricing water resources and water sanitation services* (Paris: OECD, 2010).

OECD, *Pricing Water Resources and Water Sanitation Services* (Paris: OECD, 2006)

Olmstead, S. M. (2010) “The economics of managing scarce water resources” *Review of Environmental Economics and Policy* Vol. 4, No. 2 (2010): 179–98.

Pigram, J.J. (1993) "Property rights and water markets in Australia: An evolutionary process toward institutional reform" *Water Resources Research* Vol. 29, No. 4 (1993): 13–19.

Popp, D. (2006) “International innovation and diffusion of air pollution control technologies: The effects of NOX and SO2 regulation in the US, Japan, and Germany” *Journal of Environmental Economics and Management* Vol. 51: 46-71.

Popp, D. (2011) “International technology transfer, climate change, and the clean development mechanism” *Review of Environmental Economics and Policy* Vol. 5 (2011): 131-152.

Purohit, P. and Kandpal, T. (2005) "Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery and investment requirements using available diffusion models" *Renewable and Sustainable Energy Reviews* 9 (2005): 592–607.

Rijsberman, F. R. (2006) “Water scarcity: Fact or fiction?” *Agricultural water management*, 80(1), 5-22.

Seckler, D. W. (1998) “*World water demand and supply, 1990 to 2025: Scenarios and issues (Vol. 19)*.” IWMI.

Speight V. L. (2015) “Innovation in the water industry: barriers and opportunities for US and UK utilities.” *WIREs Water* 2015. doi: 10.1002/wat2.1082

UNDP (2006) “*Human Development Report 2006: Beyond Scarcity: Power, poverty and the global water crisis.*” New York: United Nations Development Programme.

UNICEF (2010) "Progress on Sanitation and Drinking-water: 2010 Update" WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2010.

Verdolini, E. and M. Galeotti (2011) "At home and abroad: An empirical analysis of innovation and diffusion in energy technologies." *Journal of Environmental Economics and Management* 61 (2011):119-134.

Wehn, U. and Montalvo, C. (2014) “Exploring the dynamics of water innovation.” *Journal of Cleaner Production* 87, 3-6.

APPENDIX: PATENT CLASSIFICATION CODES USED TO CONSTRUCT THE DATASET

DEMAND-SIDE TECHNOLOGIES

1-Water efficiency – domestic	
Self-closing valves	
Self-closing valves, i.e. closing automatically after operation, in which the closing movement, either retarded or not, starts immediately after opening	F16K21/06-12
Self-closing valves, i.e. closing automatically after operation, closing after a predetermined quantity of fluid has been delivered	F16K 21/16-20
Aeration of water	
Arrangement or mounting of devices, e.g. valves, for venting or aerating or draining	F16L 55/07
Jet regulators with aerating means	E03C 1/084
2- Sanitation	
Dual-flush toilets	
Flushing devices discharging variable quantities of water	E03D 3/12
Flushing cisterns discharging variable quantities of water	E03D 3/14
Dry toilets	
Urinals without flushing	A47K 11/12
Dry closets	A47K 11/02
Waterless or low-flush urinals; Accessories therefor	E03D13/00E
Closed-circuit toilets	
Special constructions of flushing devices with recirculation of bowl-cleaning fluid	E03D5/016
3- Piping – reducing leakage & leakage monitoring	
Pipe-line systems / Protection or supervision of installations / Preventing, monitoring, or locating loss	F17D 5/02 and E03
Devices for covering leaks in pipes or hoses, e.g. hose-menders	F16L 55/16 and E03
Investigating fluid tightness of structures, by detecting the presence of fluid at the leakage point	[G01M 3/08 or G01M 3/14 or G01M 3/18 or G01M 3/22 or G01M 3/28] and E03
4- Water efficiency in power production	
Combustion heat from one cycle heating the fluid in another cycle	F01K 23/08-10

Non-positive-displacement machines or engines, e.g. steam turbines / Preventing or minimising internal leakage of working fluid, e.g. between stages	F01D 11
5- Drip irrigation	
Watering arrangements located above the soil which make use of perforated pipe-lines or pipe-lines with dispensing fittings, e.g. for drip irrigation	A01G 25/02
Watering arrangements making use of perforated pipe-lines located in the soil	A01G 25/06
6- Control of watering	
Control of watering	A01G 25/16
7- Drought-resistant crops	
Mutation or genetic engineering; DNA or RNA concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification; for drought, cold, salt resistance	C12N15/82C8B2
8- Greywater	
Greywater supply systems	E03B 1/04B

SUPPLY-SIDE TECHNOLOGIES

1- Underground water collection	
Use of pumping plants or installations	E03B 5
Methods or installations for obtaining or collecting drinking water or tap water from underground	E03B 3/06-26
2- Surface water collection	
Methods or installations for drawing-off water	E03B 9
Methods or installations for obtaining or collecting drinking water or tap water from surface water	E03B 3/04; 28-38
3- Rainwater water collection	
Methods or installations for obtaining or collecting drinking water or tap water from rain-water	E03B 3/02
Special vessels for collecting or storing rain-water for use in the household, e.g. water-butts	E03B 3/03
4- Storage	
Arrangements or adaptations of tanks for water supply	E03B 11
5- Desalination	
Desalination of sea water	An EPO tag