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Joint Working Party on Agriculture and the Environment

STATUS AND CHARACTERISATION OF GROUNDWATER RESOURCES IN AGRICULTURE IN OECD COUNTRIES

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This report is presented for DISCUSSION at the 37th meeting of the Joint Working Party on Agriculture and Environment, to be held from 14 to 15 April 2014.

Item 6a) of the draft agenda.

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NOTE BY THE SECRETARIAT

This paper is an interim report for the project on groundwater use in agriculture under output 3.2.3.1.3 of the 2013-14 Programme of Work and Budget of the Committee for Agriculture on water and climate change adaptation. The project was discussed in the November 2013 meeting of the Joint Working Party on Agriculture and Environment [COM/TAD/CA/ENV/EPOC(2013)52]. The paper includes a draft introduction to the overall report and a first section on the status and characterisation of groundwater resources in agriculture in OECD countries. It will be followed by sections on the economic and policy aspects to be completed at a later date.

This paper is submitted for **DISCUSSION**.

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EXECUTIVE SUMMARY

Groundwater resources have allowed major gains in global agriculture productivity and continue to sustain a significant share of global crop production. Initially used in very limited areas in a few countries in the early 20th century, groundwater now represents over 40% of consumptive irrigation water use, covering just under 40% of irrigated land globally. The scope of use and significance of groundwater can largely be explained by its intrinsic characteristics, including in particular its insulation from weather-related events, the role it can have as a natural storage facility, and the advantage of providing water on demand to individual farmers that have access to it.

However, these advantages, coupled with increased use from competing sources of demand, have contributed to increase its use beyond natural recharge in many regions. Such overdrafting can affect its use by farmers in the future, and in some cases also induces significant environmental damages. Exploiting groundwater resources beyond recharge is bound to affect users of irrigated agriculture first; lowering water tables, which increases the cost of pumping and creates a race to the bottom among competing producers. It can also generate environmental effects with direct and sometimes irreversible consequences on ecosystems with implication for future water uses.

This report serves as the first part of a three-part project on groundwater in agriculture, whose objective is to provide a comprehensive analysis of the economics and policies underpinning the growing and diverse challenges of groundwater resource management in agriculture in OECD countries. A number of OECD reports include sections, sub-section, paragraphs, or illustration that relate to groundwater, but they do not convey policy conclusions specifically geared towards the managers of specific types of groundwater, especially in the context of agriculture.

More specifically, this report analyses agriculture groundwater use and irrigation systems in OECD countries. Drawing on existing knowledge, it first synthesizes existing data on the groundwater resources and their use in agriculture. It then proposes a characterisation of groundwater irrigation systems to try and capture the heterogeneity of aquifers when considering economic and policy issues. Lastly, it reviews the main challenges associated with the use of groundwater in agriculture.

A review of available data shows both the importance and heterogeneity in groundwater use across OECD countries. Groundwater irrigation is used on an estimated 23 million hectares in OECD countries, which represents one third of the OECD total irrigated area. As of 2010, 60% of total groundwater withdrawal in OECD countries (or 229km^3/year) was used for irrigation, which represents about a third of total groundwater irrigation globally. These area and volume totals are largely driven by around ten OECD countries, located mostly in North America and the Mediterranean region, where groundwater is primarily used in semi-arid areas. But other OECD countries also use groundwater significantly, sometimes in complement with surface water.

Agriculture use is growing and contributing to groundwater stress. Incomplete data on trends shows that some of the leading groundwater irrigating countries in OECD have increased their use over the past 25 years, while others may have oscillated around an average. The OECD average groundwater development stress (GDS) for agriculture, which measures the ratio of use over natural recharge, was estimated at 7.6% in 2010, with large variations across members, ranging from zero to over 100%. Climate

projections, that remain limited in scope due to data uncertainties, still point towards reduced recharge, including in some of the major aquifers used by agriculture in OECD countries.

While these figures can be assessed at the national level, groundwater is essentially a local resource, whose characteristics greatly depend on specific conditions and use at the aquifer level. This heterogeneity raises the question of how management challenges can be analysed and lead to meaningful responses without oversimplifications. Based on a review of existing geographic, geological and socio-economic typologies, a generic characterisation is proposed for groundwater irrigation systems in OECD countries with the goal of serving as a basis to differentiate management and policy responses. Agro-climatic conditions, relative access to and availability of surface water, access to and availability of usable groundwater resources and trends in groundwater use and profitability compared to competing demands from other sectors are identified as the four main factors to be considered. Each of these four factors is then linked to primary and secondary variables, notably geographic, geological, and hydrogeological considerations.

Lastly, the main challenges associated with groundwater use are reviewed. The use of groundwater irrigation can generate important external effects both on agriculture and the environment. Beyond increases in pumping costs and directly related environmental externalities, the large and irreversible economic consequences associated with salinity and land subsidence are discussed. While each of these phenomena is found in multiple OECD countries, they are associated with specific groundwater irrigation systems.

The continued use of aquifers that are under pressure and facing significant environmental issues, throws into question current management practices and has important implications for the future of groundwater and irrigated agriculture. The two parts of the report to follow, will, in focussing on economic considerations and reviewing current and potential policy options, analyse these aspects, taking into account the presented diversity of contexts.

INTRODUCTION

1. Groundwater can be defined as "*water contained in an aquifer matrix located beneath the surface in the saturated zone, as opposed to free surface water bodies like streams, reservoirs, or lakes*" (Siebert et al., 2010).[1] It is constituted of the underground water that "*fully saturates all fissures and pores below the earth's surface*" (Giordano, 2009). As such, it occupies a specific part of the water cycle, connected but often semi-independent from surface water. Overall, groundwater represents a major portion of usable water resources, accounting for 96% of liquid freshwater (UNESCO, 2008). While it is often used as a complement to surface water, groundwater is a significant source of public water supply; about 60% of total drinking water used for human consumption (Margat, 2008). It also provides crucial support to agriculture and industrial activities in multiple countries. Overall, over 2.6 billion people may rely on groundwater resources (OECD, 2012a).

2. The importance of groundwater for agriculture irrigation is well documented (Giordano and Villholth, 2007). More than 60% of groundwater use is for agriculture in semi-arid and arid regions, producing 40% of the world's food (Morris, 2003; OECD, 2012a). Globally, Shah et al. (2007) estimated that agriculture groundwater supported an annual output equivalent to USD 210-230 billion, corresponding to an average gross productivity of USD 0.23- 0.26/m^3 abstracted. Total consumptive groundwater use for irrigation in 2010 was estimated as 545 km^3/year, or 43% of the total consumptive irrigation water use (Siebert et al., 2010). The total area used for groundwater irrigation covered 98 million ha or 39% of the total irrigated land in 2010 (Siebert et al., 2010). Given that they focus on groundwater sources alone, these estimates are likely undervalued, because groundwater is very often used in conjunction with surface water for irrigation (Kemper, 2007).

3. Groundwater resources have allowed major gains in global agriculture productivity and continue to sustain a significant share of global crop production (OECD, 2010a and 2012b). The spectacular expansion in groundwater irrigation in the past four decades has been termed a "silent revolution", resulting in large effects on agriculture production levels (Garrido et al., 2005). Groundwater development for irrigation started in Italy, Mexico, Spain and the United States and was followed by rapid expansion primarily in Asia (Shah et al., 2007; van der Gun, 2012). It now accounts for half of South Asia's irrigation and supports two thirds of grains supply in China (Giordano and Villholth, 2007). It also plays a significant role in agriculture in OECD countries, especially those with arid or semi-arid conditions. Over 60% of irrigated agriculture and nearly half of the farmers use groundwater in the United States (Gollehon and Quinby, 2006; Scanlon et al., 2012). It represents over 70% of Spain's irrigation, and was shown to provide five times more value and three times more jobs than irrigation from surface water in the region of Andalucía (Hernandes-Mora et al., 2003). Groundwater also provides a third of the water used for irrigation in Mexico, which is the largest user of groundwater in Latin America, with over 100 000 large-capacity pumps (Scott et al., 2010). And its use in agriculture is estimated to contribute AUSD 11 billion annually to the Australian economy (Deloitte Access Economics, 2013).

4. The scope of use and significance of groundwater can largely be explained by its intrinsic physical characteristics. First, unlike surface water, it is characterized by high storage relative to inflows (Giordano, 2009). Second it flows at a much slower pace than surface water (OECD, 2011b). Combined

1 The portion of earth that supports groundwater is known as an aquifer (Giordano, 2009).

with the very wide coverage it has globally and the general insulation it provides from chemicals and weather changes, its utility is often compared to that of a natural reservoir at the global scale, constituting a type of “buffer storage” that can complement surface water (Morris et al., 2003). The low rates of inflows and outflows to groundwater reserves assure the viability of the resource even in time of drought (Bovolo et al., 2009; OECD, 2011b).

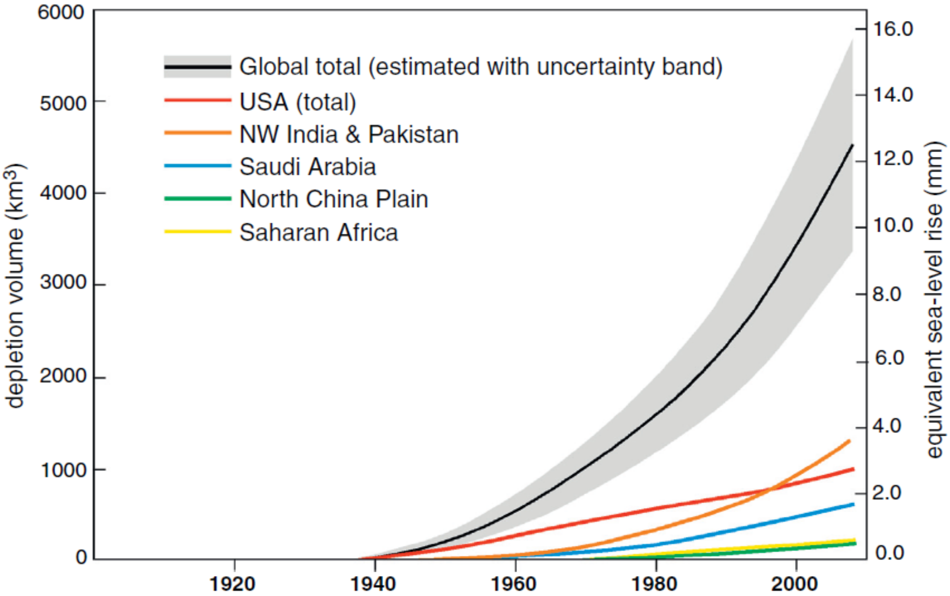
5. Groundwater is effectively used in agriculture as a natural storage facility, acting as insurance against drought (Garrido and Iglesias, 2006), enabling producers to sustain the use of water when surface water is not sufficient. In arid and semi-arid areas, groundwater irrigation provides longer growing seasons and lower risks of pest and disease (Siebert et al., 2010). Its capacity to serve as a reservoir also makes it an important tool to increase long term resilience to climate change (Green et al., 2011; Gleeson and Cardiff, 2013; OECD, 2013e).

6. Groundwater is also used, even in less climate-stressed areas, by individual farmers of small to large size due to its ability to provide “water on demand”– i.e. letting producers manage their water depending on their needs (OECD, 2010b). Groundwater resources are characterized by their *horizontal* dimension, with aquifers covering large areas not always contiguous with surface water basins, allowing farmers to access water under their field independently from others, in a rather equitable manner (Kemper, 2007). In multiple areas, with shallow aquifers, it is furthermore easy and relatively cheap to access thanks to the development of cheap pumping technologies. As a result, it is seen by farmers as an attractive, reliable, and easily accessible source of water (Garrido and Iglesias, 2006), and is highly popular among farmers (Garduño and Foster, 2010).[2]

7. However, these advantages have contributed to increase its use beyond natural recharge in many regions. Even if global groundwater reserves remain large (Margat, 2008), and are only declining minimally (Famiglietti and Roddell, 2013), virtually all studies show that there has been a rapid increase of groundwater use (Giordano, 2009); as shown in Figure 1. This is especially the case for agriculture, where use has increased both in relative and absolute terms, contributing to an accelerated lowering of the water table in a number of regions (Garrido et al., 2005; Siebert et al., 2010; OECD, 2010a; Margat and van der Gun, 2013). While agriculture is a significant contributor to the recharge of shallow aquifers (Taylor et al., 2012), it has increasingly become an even larger withdrawer of groundwater. Non-renewable abstraction reached 234 km^3/year or 20% of gross irrigation demand in 2000, and had more than tripled in size since1960 (Wada et al., 2012). Due in part to increased climate variability, affecting access to surface water, groundwater resources are increasingly used to the point of being exploited beyond recharge in multiple agricultural regions (Taylor et al., 2012).

2 Indeed, several studies in different countries have shown the systematic preference of farmers for groundwater irrigation (Shah, 2009).

Figure 1. Groundwater cumulative use: total depletion volume and equivalent sea-level rise



Source: Foster et al. (2013).

8. Exploiting groundwater resources beyond recharge, or "overdrafting"[3], is bound to affect users of irrigated agriculture first. Groundwater use is considered "*one of the most important challenges for agriculture*" (OECD, 1998; 2011b). As noted by FAO (2011), "*because of the dependence of many key food production areas on groundwater, declining aquifer levels and continued abstraction of non-renewable groundwater present a growing risk to local and global food production.*" Continued abstraction results in lowering water tables, which increases the cost of pumping and creates a race to the bottom among competing producers. In Mediterranean countries in particular, aquifers that contribute largely to drinking water supplies, are exploited by farmers beyond their recharge rates (OECD, 2011c). But continued overdrafting is also bound to affect countries where groundwater is not a major source of irrigation via market linkages; the gradual depletion of groundwater resources especially in South and East Asia, on an agricultural land that feeds hundreds of millions of people, may have global food security consequences with trade and production implications (Wada et al., 2012).

9. Groundwater overdrafting also affects the environment (OECD 1998; 2011a), and can generate environmental effects with direct consequences on agriculture production. In particular, it can result in land subsidence and increased salinity (Bovolo et al., 2009). In Mexico and Western United States, it has resulted in significant land collapses (Foster, 2008; Sneed et al., 2013). Groundwater pumping can also result in desiccation of natural reserves, as seen in the Netherlands, and contribute to drying up of wetlands, as seen in Southern Europe, with significant loss for water quality filtering (Hellegers et al., 2001; UNECE, 2011). Significant pumping in coastal aquifers, or aquifers connected to saline water bodies is a significant source of salinization of groundwater, affecting the crop choice for agriculture and ecosystems in the wetlands, rivers and ponds to which it is connected (Schoengold and Zilberman, 2007; Fuentes, 2011; UNECE, 2011; Amores et al., 2013).

10. Lastly, overdraft of groundwater resources can affect the future use of this resource for agriculture. Under such exploitation path, an option value is lost for farmers. It is estimated that 97% of the

3 The term groundwater depletion is also used to represent the same phenomenon (e.g. OECD, 2012b).

groundwater, via run-offs, evapotranspiration and precipitation, ends up in oceans (Wada et al., 2010), and a number of years can be needed to recharge the aquifer, assuming its capacity remains unchanged. In extreme cases, especially under arid conditions, where surface water is not easily available, situations of "boom and bust" can result in agriculture reaching a no return water level, under which it is no longer profitable to farm.

11. A number of OECD reports have looked at specific aspects of groundwater policies, as part of more general studies of water resource management, but none of these reports specifically addressed the intrinsic challenges it faces. Reports on water have for instance provided general principles for sustainable water management (OECD, 2010b) and discussed the use of economic instruments (OECD, 2011b). Groundwater has been discussed in the context of pricing and financing (OECD, 2009a and 2009b), energy (OECD, 2010a), risk management (OECD, 2013e), and broader perspectives covering climate change (OECD, 2013a and 2013e). Groundwater is also featured in the reviews of water reforms at the country level (see, e.g. Fuentes, 2011; OECD, 2013b). All these reports include sections, sub-sections, paragraphs, or illustrations that relate to groundwater, but they do not convey policy conclusions specifically geared towards the managers of specific types of groundwater, especially in the context of agriculture.

12. Several common threads can be identified in the broader literature on agriculture and groundwater. First, a consistent observation is that groundwater is generally under-studied and there is a need for more in-depth assessment of groundwater resources stocks, use, and management practices. Insufficient knowledge on resource flows and management practices is seen as problematic to address pending challenges in a number of regions (see, e.g. Struzik, 2013). Second, several reports and articles identify groundwater policies as an area requiring further in-depth analysis (Koundouri, 2004; OECD 2007; 2010b). And third, the specific types of aquifer and their respective constraints are emphasized as having a critical role in the determination of sustainable management plans for agriculture (Giordiano and Villholth, 2007).

13. This project will try and respond to these calls, by looking in a systematic way at quantitative groundwater management challenges for agriculture and the potential role of policies, accounting for the different types of aquifers. The objective of the project is to provide a comprehensive analysis of the economics and policies underpinning the growing and diverse challenges of groundwater resource management in agriculture in OECD countries.

14. As a caveat, the analysis will focus almost entirely on groundwater use associated with irrigated agriculture. This means in particular that livestock water consumption will not be extensively analysed, notably because of the lack of data and information. This also means that the management of excessive groundwater levels, not related to agriculture use, but affecting agriculture, will be left out of the discussion.[4] Lastly, qualitative challenges will also not be discussed, except when directly related to groundwater use (e.g. salinity). Other agriculture induced quality issues, including nitrogen filtration into aquifers, are left for future endeavours.

15. This interim report covers one of three sub-objectives of the project. It provides a synthetic review on where OECD countries stand in terms of groundwater resources and agricultural use, the specific characteristics of aquifers encountered, and the main issues they currently face and will face in the future. The second and third parts of the project, not included in this report, will provide an economic analysis of groundwater use, and assess current and potential policy options for agriculture groundwater management.

4 The extent of groundwater drainage for agriculture use and managing floods will not be reviewed in details, see OECD (2013d) for more thorough information on that issue.

STATUS AND CHARACTERISATION OF GROUNDWATER RESOURCES IN AGRICULTURE IN OECD COUNTRIES

16. If groundwater is recognized as the largest component of available freshwater, playing a major role for agriculture globally, it is also fundamentally defined as a locally-specific resource (Campana, 2014). There is a large heterogeneity in the hydrogeological nature of aquifer systems at the global scale, which, combined with diverse agro-climatic conditions, production patterns and practices, translates into multiple types of groundwater irrigation systems.

17. This global heterogeneity questions the possibility of making any valid judgment on agriculture groundwater management at the national or international scale. As noted in one of the early studies of agriculture groundwater management (Snyder, 1955: vii): "*The economic implications of ground water hydrology and ground water law are best developed through detailed studies of the experience in selected ground water basins*". Indeed, the United Nations Food and Agriculture Organization (FAO) once questioned the usefulness of developing a global picture of groundwater resources, given the local emphasis of its challenges (Giordano, 2009). If each aquifer-agricultural combination differs from the next, not much could be said in general about their constraints, and even less about their management.

18. Yet, the increased knowledge of hydrogeological conditions, the similarities in groundwater pumping patterns and technologies, and the multiplication of national, regional and local case studies have made the exercise increasingly more plausible. Using available country data, the FAO has developed a set of national groundwater variables as part of the Aquastat database (Siebert et al., 2010).[5] Multiple international projects have been conducted with the goal of characterizing and assessing groundwater resources at the global scale (e.g. see van der Gun, 2007). The United Nations Economic, Social and Cultural Organization's International Hydrological Program (UNESCO-IHP), the Global Water Partnership, and the common platform set up by the International Groundwater Resources Assessment Centre (IGRAC), among other programs, underline the benefits of trying to have a comprehensive overview for local cases.[6] Furthermore, projects led under the World Bank's Groundwater-Management Advisory Team (GW-MATE) have studied the use of groundwater in agriculture in several developing countries, finding some relatively generalizable cross-country conclusions (Foster and Garduño, 2013).

19. This section discusses the balance between locally-specific constraints and conditions around the use of groundwater in agriculture, and common patterns at the regional, national, or supranational level, focusing on OECD countries. The overall objective of the section is to provide a review of knowledge about the status and evolution of groundwater use in agriculture in OECD countries, but also to attempt to characterize the types of aquifers and to review the related constraints for agricultural groundwater management in a tractable and consistent manner.

20. The analysis is based on collected available information and data on the status and use of groundwater resources in agriculture in OECD countries. It has been complemented by consultations with

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5 Available at: http://www.fao.org/nr/water/aquastat/main/index.stm

6 For more information on UNESCO-IHP, see http://www.unesco.org/new/en/natural-sciences/environment/water/ihp, for GWP: http://www.gwp.org/ and for IGRAC: http://www.un-igrac.org/. See van der Gun (2007) for a list of other institutions.

several water experts.[7] Still, the exercise is not completed and intended to be further refined with inputs from an OECD country questionnaire to be disseminated in the spring of 2014.

21. The rest of the report is organized in three parts. A first part reviews available data on groundwater resource and use in OECD countries. The second part addresses the question of commonalities and differences, reviewing existing typologies, and proposing a characterisation of aquifers used in agriculture in OECD countries. The third part reviews the main constraints and challenges for groundwater agricultural systems in OECD countries.

Groundwater resources and use in agriculture

Available and unavailable information

22. Due to its largely non-visible nature, the complexity of hydrogeological situations, the intrinsic specificity of each aquifer, and the related difficulty of measuring its state and flows, groundwater is often considered an "invisible" resource (Monginoul and Rinaudo, 2013).[8] Multiple tools have been developed to assess groundwater quantity, yet the lack of investment in measurement, coupled with improving but still imperfect analytical tools to provide updated information make the assessment of groundwater resources often incomplete or obsolete in multiple OECD countries (e.g., Struzik, 2013). The fact that measuring groundwater is difficult and expensive and that data are not always shared further contribute to the general apparent lack of reliable knowledge on its status and uses (BGS, 2009).

23. If groundwater flows could be assumed to be easier to measure than stocks given the intrinsic complexity of aquifer structures, it is in fact at least-if not more-difficult to assess precisely the flows in and out of aquifers in a comprehensive manner (Giordano, 2009). On the discharge side, natural uses and flows operating both vertically and horizontally in aquifers increase the complexity of the picture. The lack of monitoring and/or reporting on pumping in many countries also plays a significant role, especially in agriculture. Different types of monitoring tools also can lead to divergent results, as observed in the case of irrigation data in Arizona (Cohen et al., 2013). At the same time, recharge measurement is very difficult to assess given the differences in situations, soil profiles and soil covers and connections with surface water bodies. Field crop activities are known to participate actively to recharge in many cases, even sometimes much more significantly than natural ecosystems (Taylor et al., 2012), but specific local constraints once again make generalisations challenging.

24. Measurement efforts combining different type of local and regional measurements, including via satellite based tools, appear to have improved assessments, but remain imperfect. Satellite data, including that generated by the US NASA's Gravity Recovery and Climate Experiment (GRACE) has been able to provide overall monthly and yearly changes in groundwater stock in multiple regions. It demonstrated in particular the diminution in resources in California over time (e.g., Famiglietti et al., 2011). But the resolution remains insufficient, it depends on significant periods of time and its use requires complementary traditional measurements.

25. The picture on available resources and data is therefore mixed. Smaller countries, with more homogeneous geological profiles under agricultural land, where data is collected and shared, are able to track groundwater resources well over time (e.g. Denmark). Larger countries with more numerous

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7 This includes researchers from the International Water Management Institute, the International Food Policy Research Institute, the Pacific Institute, and universities (Georgetown, Oregon State and Wageningen).

8 As Giordano (2009) points out, this invisible resource has still been the object of the silent revolution, illustrating the difference in perspective between farm level resource extractions and larger scale diagnostics.

institutional contexts, significant investments, but not always functioning data sharing mechanisms, may have general information overall, with more detailed monitoring on groundwater hotspots (e.g. USA). Lastly, humid countries, for which groundwater is not as important a resource, and with predominantly rainfed agriculture, do not dedicate many resources to groundwater quantity measurement, resulting in a general lack of information (Canada, e.g. see Council of Canadian Academies, 2013:93).

26. With these caveats in mind, affecting both overall availability and reliability, the following section provides information on groundwater resources and agricultural use based on available secondary data, mostly relying on estimates and assumptions rather than actual measurement.

Groundwater resources use in agriculture

27. The first variables of interest are the overall state of resources or groundwater endowment. Table 1 provides range of estimates for the groundwater stocks, inflows and withdrawals, based on different analytical estimates of water resources (Margat and van der Gun, 2013). Groundwater reserves are estimated to be over 20 million km^3, of which 40% is freshwater. Annual recharge amounts to around 12 thousand km^3, while annual withdrawal ranges between 600-1100km^3, with recent estimates ranging between 950 and 1000 km^3 (OECD, 2009b; van der Gun, 2012; Margat and van der Gun 2013).[9]

Table 1. Ranges of estimates of global groundwater stocks, inflows and withdrawals

	Type	Estimates (km^3)	Share of total stock
Stocks	Freshwater	8 to 10 million	~40%
	Brackish or saline water	12 to 14 million	~60%
	Total	20 to 24 million	100%
Annual recharge	Total	11 to 15 thousand	0.05-0.08%
Annual withdrawal	Total	0.6 to 1.1 thousand	0.0025-0.0055%
	Agriculture irrigation only	0.545-0.688 thousand	0.0023-0.0034%

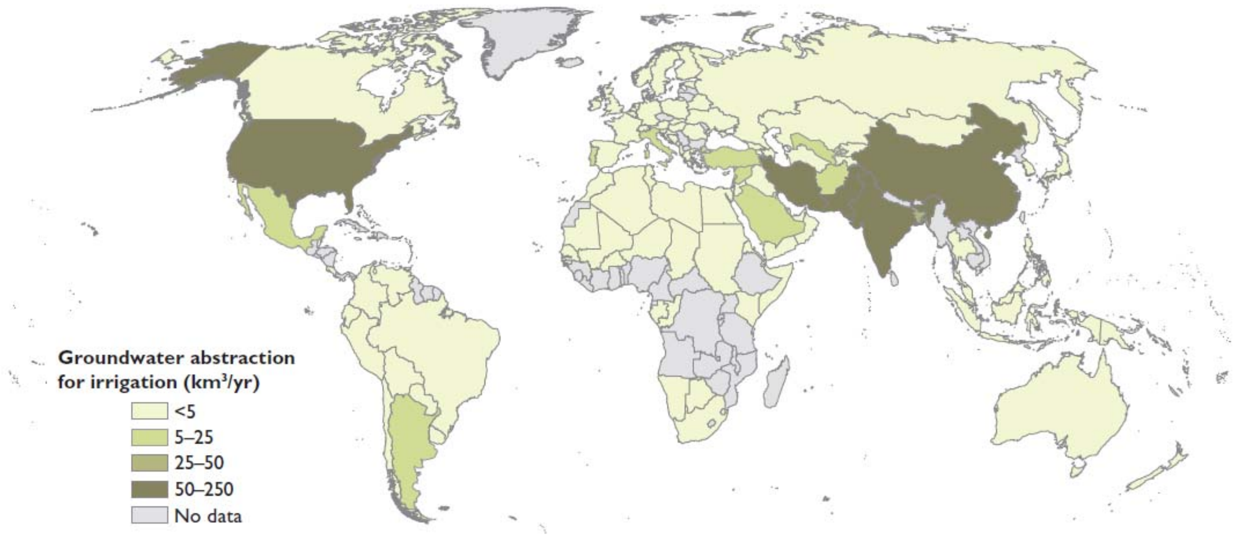
Source: Margat and van der Gun (2013) based on a review of existing estimates for stocks and recharge, Siebert et al. (2010), van den Gut (2012) and Margat and van der Gun (2013) for agriculture.

28. Agriculture uses groundwater primarily for irrigation but also as a drinking resource for livestock. Most available figures on groundwater use focus solely on irrigation, hence the emphasis on irrigation in this analysis (see Annex for livestock data, which is often limited, as noted in Deloitte Access, 2013). Globally, irrigation accounts for two thirds of groundwater withdrawals, with total estimates ranging between 545 and 688 km^3/year (Siebert et al., 2010; Margat and van der Gun, 2013). Taking the 545 km^3 estimate, this accounts for about 43% of total irrigation.

29. Despite evidence of local water risks in the future, these figures show that the global use of agricultural irrigation is relatively insignificant, representing about 5% of annual natural inflows, and only 0.003% of total groundwater reserves. At the same time, Table 1 also shows that agriculture accounts for a very large share of total withdrawals, amounting to an estimated 70% in 2010, although at different rates internationally, as shown in Figure 2 (Margat and van der Gun, 2013). Competing uses include industry and public water supplies- in many regions, groundwater is the sole source for drinking water.

9 Margat and van der Gun (2013), who look at different sources, estimate withdrawals to be 982 km^3/year as of 2010.

Figure 2. Groundwater withdrawal rates for irrigation



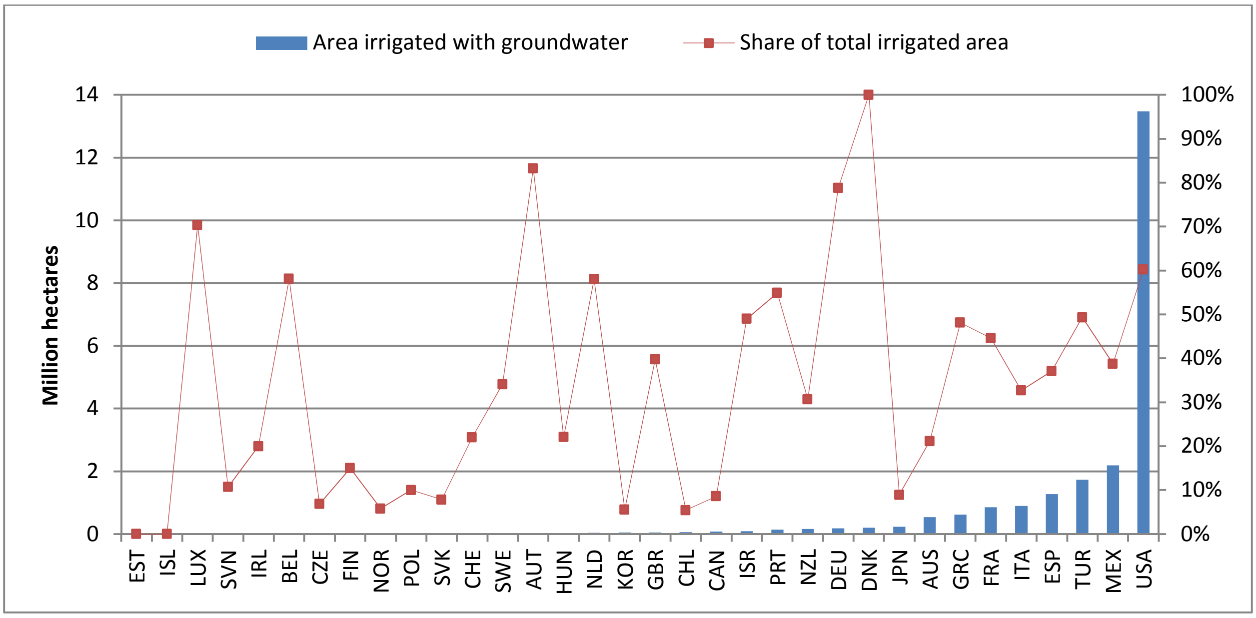
Source: Margat and van der Gun (2013).

30. Moving at a lower level, estimates of groundwater irrigated areas and shares of total irrigated areas in OECD countries are shown in Figure 3, while similar data for withdrawals for the reference year 2010 are shown in Figure 4.[10] Groundwater irrigated area in OECD covers about 23 million hectares, or about 26% of the global irrigation figures, estimated to be 89 million ha (Siebert et al., 2010). More than half of OECD's groundwater irrigation is located in the United States. Mexico, Turkey, Spain, Italy, France, Greece and Australia follow, with at least 500,000 ha of groundwater irrigated fields. Groundwater irrigation is used to support multiple agriculture activities. Irrigated crops that use groundwater significantly include cereals and oilseeds- maize, corn, rice, soybean, wheat and cotton- in the United States (NGWA, 2013, see Table 9 in the Annex), but also sugarcane, cotton, rice and nut trees in Australia (Deloitte Access, 2013), and olive trees, vineyards, greenhouse fruits and vegetables in Spain and Greece (Garrido et al., 2005; Molinero et al., 2011; EASAC, 2010a).

31. On average, groundwater irrigated land covers 33.5% of the total irrigated areas in OECD countries, exceeding 30% or irrigated land in half of OECD countries. This exceeds previous figures from 2002, which reported that groundwater irrigation covered at least 30% in only a third of OECD countries (OECD, 2006). Shares vary from a few percent in countries with relative abundance in surface water, including Iceland, Estonia and Norway to higher shares for Germany, Austria, up to 100% for Denmark, which relies entirely on groundwater for irrigation (and drinking water). As expected, the largest irrigators in terms of area have a relatively higher share of groundwater irrigation, ranging from 35 to 60% (except Australia).

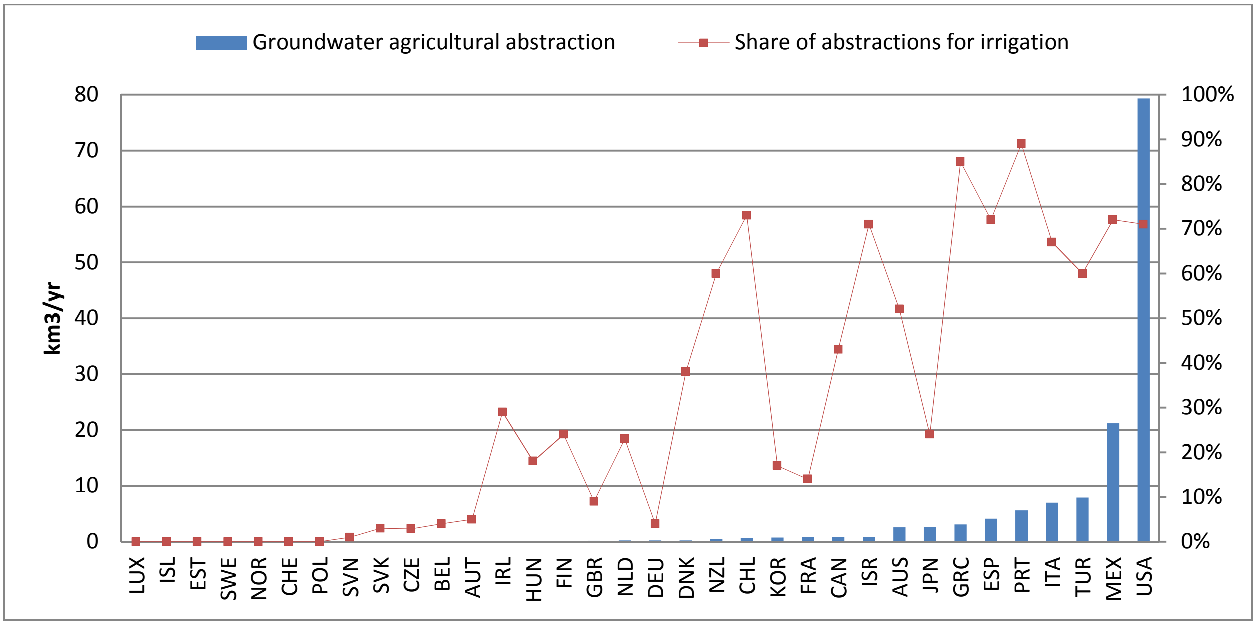
10 Data used for these figures is presented in the Annex Table 10.

Figure 3. Area irrigated with groundwater in OECD countries



Source: IGRAC (2012).

Figure 4. Estimated groundwater abstraction for agriculture irrigation as of 2010

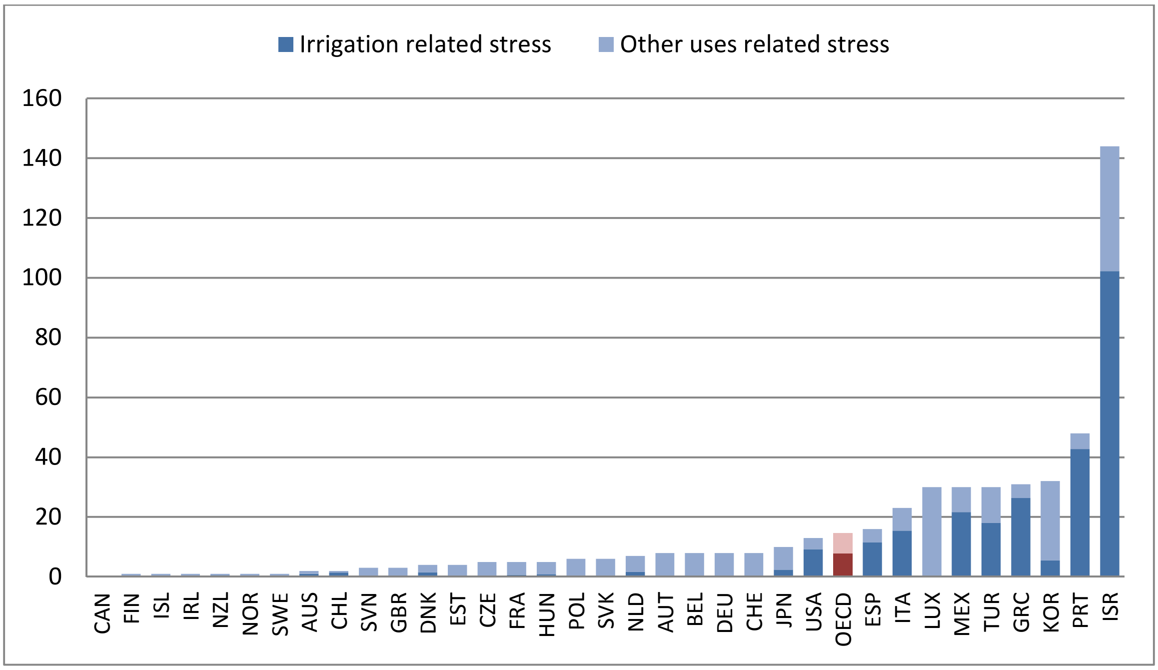


Source: Derived from Margat and van der Gun (2013), based on multiple sources. The agricultural share for Czech Republic is based on OECD (2013c).

32. Figure 4 shows national agricultural groundwater withdrawals estimated using data compiled by Margat and van der Gun (2013). [11] OECD countries' total groundwater withdrawal as of 2010 was estimated to reach 229 km^3/year, of which 60% or 139 km^3/year was used for irrigation purposes. This total represents 20% or the global groundwater use for irrigation globally (using the same estimates). The share of agricultural irrigation in total groundwater abstraction largely correlates with total agricultural withdrawals. The United States, Mexico, Turkey, Italy, Portugal, Spain and Greece have both leading irrigation withdrawals totals and agricultural shares (from 55 to 80%). Countries from Northern and Central Europe, including Poland, Switzerland, Norway, Sweden and Estonia use virtually no groundwater for agricultural irrigation.

33. While volumes and areas are indicators of the importance of groundwater for irrigation, they do not inform on the risks of overdrafting. One way of measuring groundwater resource risk is to compute groundwater development stress (GDS), which are ratios of withdrawal over recharge, providing an indication of whether resources withdrawn are likely to exceed recharge. Such country level ratios are presented for 2010 in percentages of recharge for OECD countries in Figure 5, separated into agriculture and other uses.

Figure 5. Estimated groundwater development stress (GDS) in OECD countries as of 2010 (%)



Note: the indicators are computed as the ratio of estimated groundwater abstraction (from agriculture and others) over estimated natural recharge multiplied by 100. It can be interpreted as the share of average recharge used for agriculture versus other uses.

Source: Derived from Margat and van der Gun (2013)

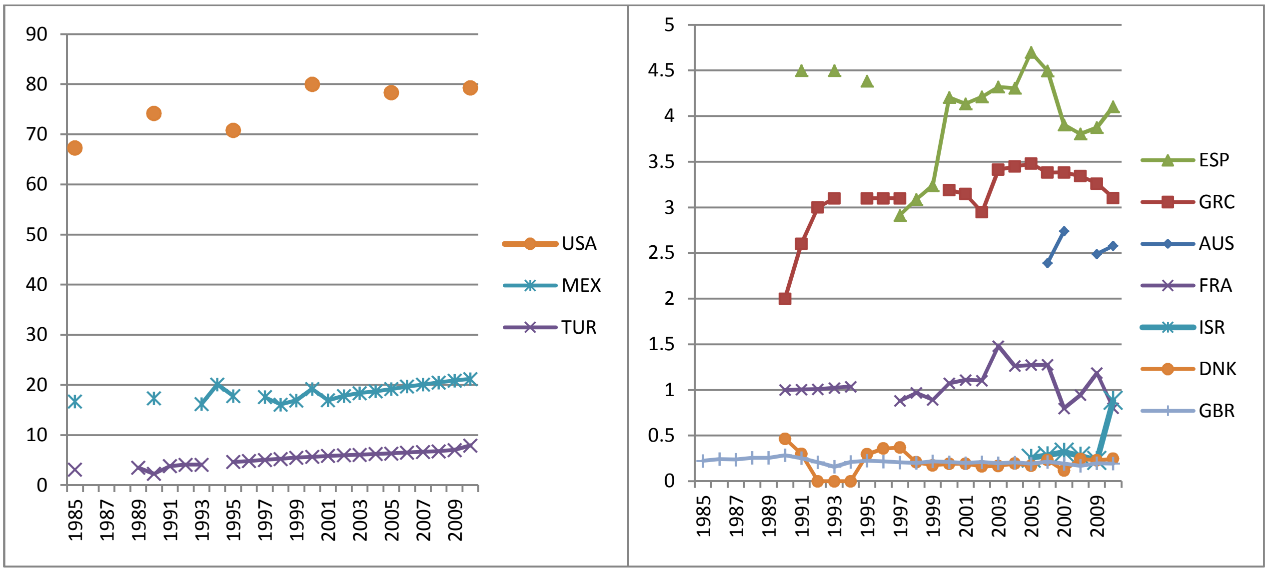
34. The OECD average GDS amounts to 14.6%, half of which (7.6%) is attributable to agriculture. Nine member countries exceed this level, including seven mainly due to agriculture use; Israel, Portugal,

11 Withdrawal figures provided in this section are based on the work of Margat and van der Gun (2013), who have reviewed all the major sources of data (including Aquastat and IGRAC), and have used those and complementary information sources to develop consistent estimates for the reference year 2010. Data collected from OECD countries as part of the agro-environmental indicators database, although consistent with those, are incomplete for multiple years, and therefore used only for trends (Figure 8).

Greece, Turkey, Mexico, Italy and Spain. The United States has a slightly lower GDS, but its agricultural GDS (9.2%) also exceeds OECD's average.[12] On the other hand, well water-endowed countries, like Canada and Northern European countries, non-surprisingly, have very low GDS. Countries in the middle, especially in Europe tend to have relatively small GDS (under 10%), and those are generally not induced primarily by agriculture use.

Figure 6. Trends in groundwater withdrawal for agriculture in selected OECD countries from 1985 to 2010 (km³/year)

Left panel: three leading OECD using countries; right panel: five middle OECD users



Source: OECD (2013c); Margat and van der Gun (2013) for 2010.

35. As a complement to the national stress indicators, Figure 6 shows the trends in use in selected OECD countries for which data was available, between 1985 and 2010. It provides a good representation of the incompleteness of data series. The United States, Mexico and Turkey are separated on the left panel for scale purposes, but these three countries also appear to be the only ones in the set of significant groundwater-using countries to have known a relative increase in withdrawals over the 25 year period. Trends in countries on the right hand side, such as Spain or Greece, present a much less identifiable pattern with fluctuations around an average use, years of increased use following years with less intensive use. Part of these changes may be due to variations in precipitations and surface water availability and access on the one hand, and on trends in competing uses on the other. Still, none of the ten countries presented here shows a significant decline in groundwater agricultural use.[13]

36. Subnational data exist in a number of countries, sometimes targeting areas of intensive groundwater uses, but compiling such data in a consistent manner is not always easy. In particular, much of the interest has been focused on the 37 major aquifers internationally, defined as large and voluminous aquifers. Not all of these are considered renewable (e.g. fossil aquifers), but this qualification has only a

12 Israel's GDS stands as an outlier, with an agricultural GDS exceeding 100%, but that total may be overvalued, given the unaccounted use of water recycling into groundwater reserves.

13 Trends for other OECD countries, with lower agricultural groundwater uses, are presented in the Annex Figure 16.

relative meaning as discussed in Box 1. Table 2 provides basic characteristics of the eight major aquifer systems present in OECD countries.

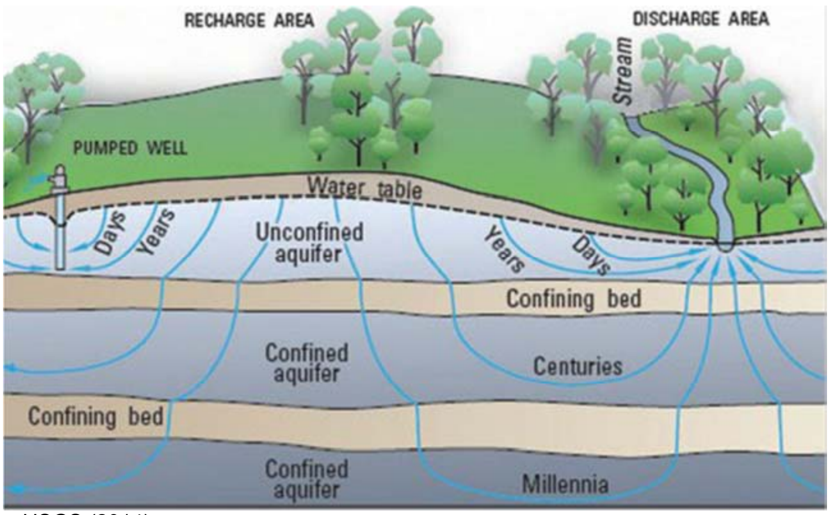
Box 1. Basic elements of groundwater flows

Groundwater is the underground body of water that fully saturates the earth, and is contained in aquifers (Margat and van der Gun, 2013). Aquifers' ceiling is called the water table, defined as the limit between the unsaturated and saturated water layer of the earth. Water tables vary largely by location but also over time depending on water flows, e.g., fluctuating naturally with seasonal rainfall, and decreasing over time with intensive pumping for irrigation.

At least two general characteristics are used to describe aquifers' structure. First, confined (or consolidated) aquifers are located below confining beds, or layers of earth that provide a relative insulation from upper layers, as shown in Figure 7. In contrast, unconfined (or unconsolidated) aquifers, that do not present such characteristics, are more openly accessed by water. Second, shallow aquifer, relatively easily accessible, are opposed to deep aquifers, that are located at much higher depth, and therefore less accessible to water and potential users.

Beyond the structure of the aquifer, the fundamental characteristics of aquifers are the stocks and flows they facilitate (Foster et al., 2013). Two properties are common to all aquifers. First, just like in the case of surface water, gravity is the main force moving groundwater from continents to water courses and oceans. Second, all aquifers have natural inflows and outflows of water, but the rates and speed of recharge and discharge greatly vary. As shown in Figure 7, short distance flows, going through shallow unconfined aquifers tend to evolve much faster than deeper long distance ones involving confined aquifers.

Figure 7. Schematic representation of groundwater discharge and recharge



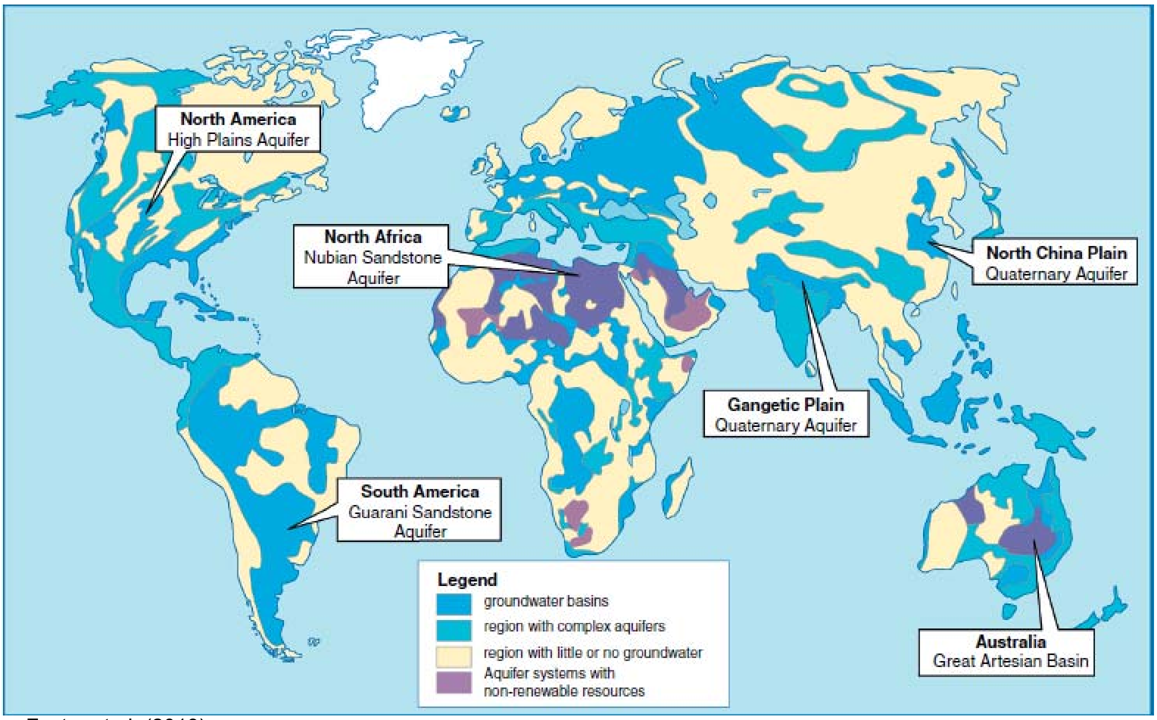
Source: USGS (2014).

A third often discussed consideration is the renewable status of specific groundwater resources. The value of such characteristic has to be interpreted in relative terms, and remains subject to discussion. All aquifers could be renewed at least partially with sufficient time under current climatic conditions, but the time it takes to renew groundwater can vary dramatically from days to hundreds of millennia. In this context, groundwater located in a very large majority of aquifers, including all those used by farmers in OECD countries can be considered renewable, with the exception of the Great Artesian Basin in Australia. Most pure non-renewable aquifers[14] are large deep and confined aquifers located in North Africa and in the Arabic Peninsula as shown in Figure 8. These groundwater bodies are also called "fossil aquifers": they were formed in the geological past, and do not receive any significant amount of recharge (Margat and van der Gun, 2013).

[14] Following Margat and van der Gun (2013), their mean renewal time (ratio of flux/reserve) is very large (1 000 to 100 000 years or more) compared to that of renewable aquifers (which may range from less than 1 to several 100 years).

Naturally, that does not prevent a number of exploited renewable aquifers in OECD countries and elsewhere to be under significant depletion. But unlike the non-renewable ones, slowing or stopping their exploitation could result in the gradual return of reserves, while the exploitation, even at a minimal rate, of non-renewable aquifers can be assimilated to irreversible mining, as in the case of minerals or fossil fuels.

Figure 8. Global distribution of groundwater resources



Source: Foster et al. (2013)

Lastly, groundwater can be extracted in multiple manners, generally split into gravity based and energy based abstraction means (Margat and van der Gun, 2013). In the first case, no energy is required for the abstraction work. Examples include drains, artesian wells, infiltration galleries and underground dams, all of which may not be feasible depending on the situation. The second category includes more conventional means for agriculture, namely dug and drilled wells for pumping that can be adapted to a larger number of cases and bring about more flexibility for management, but require a source of energy.

Source: Author, based on cited sources.

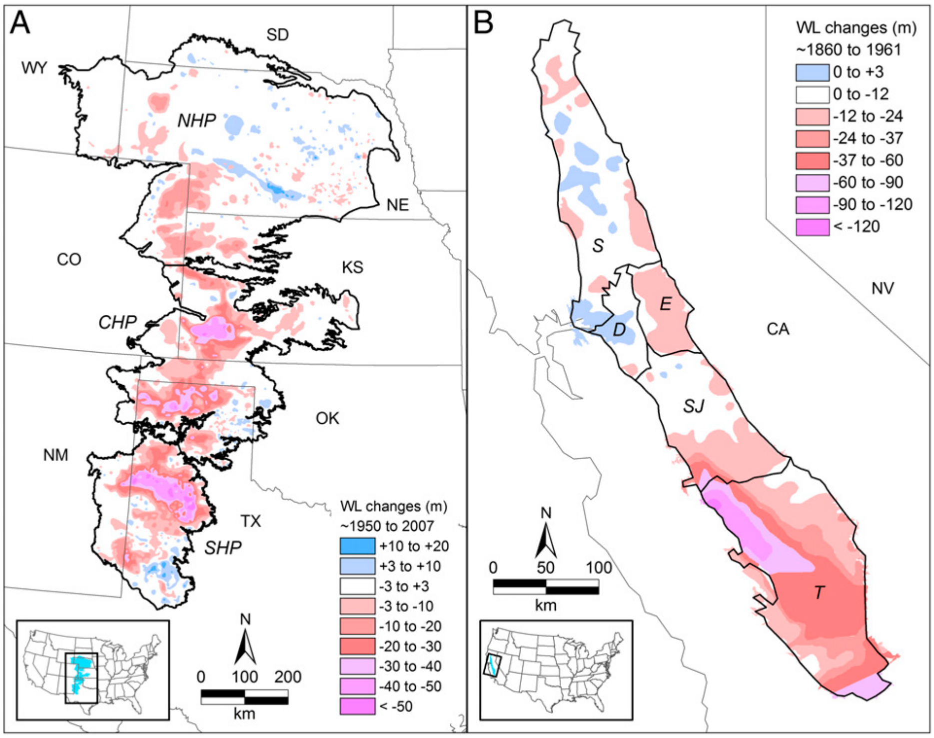
Table 2. Major aquifer systems in OECD countries

Country or countries	Name	Area (thousand km^2)	Maximum thickness (m)	Theoretical reserves (km^3)	Recharge rate (km^3/year)
Australia	Great Artesian Basin	1700	3000	20000	1.1
	Canning Basin	430	1000	n.a.	n.a.
France	Paris Basin	190	3200	500-1000	20-30
Canada and USA	Northern Great Plains Aquifer	~2000	n.a.	n.a.	n.a.
Mexico and USA	Atlantic and Gulf Coastal Plains Aquifer	1500	12000	n.a.	n.a.
USA	Cambrian–Ordovician Aquifer System	250		n.a.	n.a.
	Californian Central Valley Aquifer System	80	600	1130	7
	Ogallala (High Plains) Aquifer	450	150	~15000	6-8

Note: n.a. Not available.
Source: Margat and van der Gun (2013).

Figure 9. Changes in groundwater levels in two major U.S. aquifer systems

Left panel (A): measured change in water tables in the Ogallala Aquifer between 1950 and 2007, Right Panel (B): simulated changes in water levels in California's central valley from 1860 to 1961



Source: Scanlon et al. (2012).

37. Of these, the Ogallala (High Plains) and California Central Valley aquifer systems in the United States may be among the most studied in relation to agriculture, given the importance of agriculture use, and the overall importance of these regions for U.S. agriculture. Together, these regions have accounted for about half of total groundwater depletion in the United States since 1900 (Scanlon et al., 2012). Indeed, as shown in Figure 9, both systems have been subject to serious groundwater overdraft, with water tables lowering by up to one hundred meters in the studied period. At the same time, Figure 9 shows that the reduction in water levels depends on the location within the affected areas. In the case of the Ogallala aquifer, the central and southern parts of the aquifer (located in southwest Kansas and northern Texas) are hotspots for water level reduction, when the entire northern part of the aquifer, which benefits from more natural recharge, is not much affected, and has even seen increased water levels locally. Similarly in California, the southern San Joaquin (SJ) and Tulare (T) counties are the main hotspots for groundwater level reduction, when the northern part of the valley, with better water endowment and surface water is not really subject to groundwater depletion.

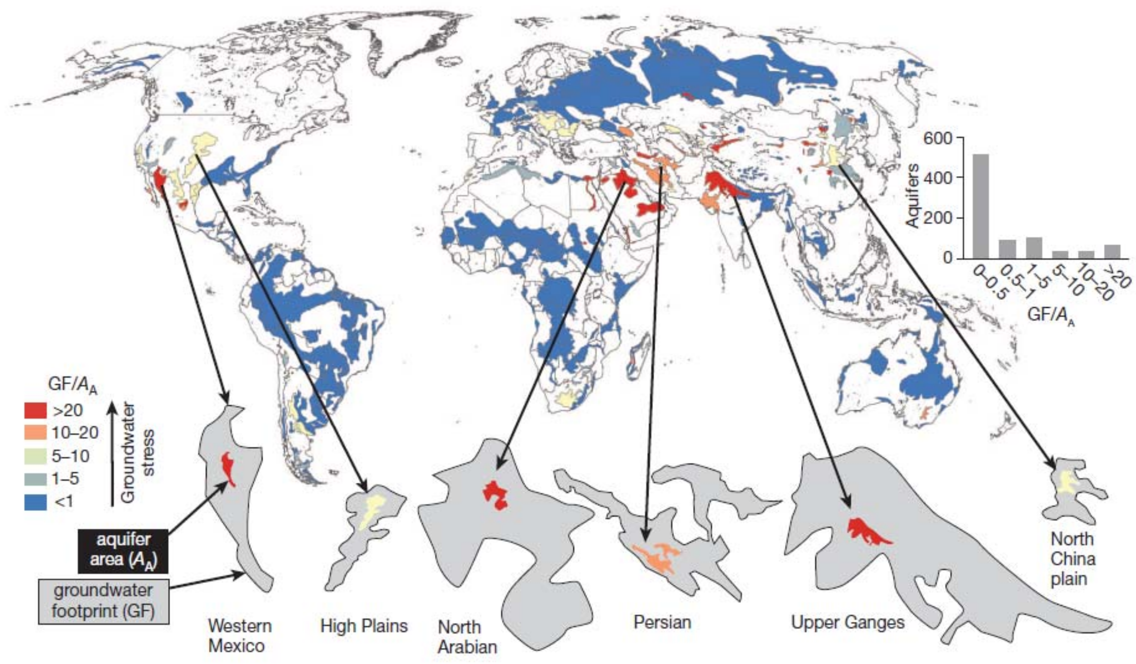
38. Stress measures have been compiled at the aquifer level. GDS have been estimated for aquifers in multiple countries as shown (using past figures) in Table 3. These figures do not separate agriculture from other uses, but many of these regions have used groundwater intensively for agricultural irrigation. Within OECD, GDS levels in largely exploited aquifer systems in Israel, Spain, Mexico, and the United States ranged from 106% in Israel to estimated 1022% for alluvial aquifers in Arizona.

Table 3. Estimated renewable global development stress (GDS) for intensively exploited aquifers in OECD countries

Country	Aquifer system	Year of estimate	Withdrawal rate (km^3/yr)	Renewable GDS
Israel	Coastal aquifer	1999-2000	0.55	178%
	Mountain aquifer	1999-2000	0.76	106%
Mexico	Valley of Mexico	1998	0.63	~200%
	Baja California	1980	0.12	150%
Spain	Mancha Occidental	1989	0.58	171%
	Campo de Cartagena	1989	0.075	231%
	Sierra de Crevillente	1989	0.015	750%
	Campo de Dalias	1989	0.11	123%
	Balearic Islands	1989	0.285	109%
	Canary Islands	1989	0.34	110%
USA	Arizona (alluvial aquifers)	1990	3.78	1022%
	Central Valley of California	1990	20	286%
	Ogallala aquifer	2000	21.5	~300%

Source: Margat and van der Gun (2013).

Figure 10. Groundwater footprint and major agriculture aquifers at risk



Source: Gleeson et al. (2012).

39. As alternative measurement, Gleeson et al. (2012) computed groundwater footprints with a specific focus on agricultural regions. These footprints are defined as the area to sustain groundwater use and ecosystem services compared with the actual area of the aquifers. Figure 10 shows a map of the ratios of footprints over the actual area of aquifers with large agricultural use, enabling to differentiate levels of risks of depletion, and in particular the latent overdraft of resources in agricultural areas of importance. Within OECD, North American aquifer systems in Mexico and the United States again, appear to have a prominent footprint and agriculture importance.

40. The effects of these reported groundwater depeletion risks on agriculture have only been studied locally in certain hotspot regions. Steward et al. (2013) studied the Kansas portion of the Ogallala aquifer. Using a simulation model, they found that without withdrawal, it would take in average from 500 to 1300 years to replenish the resource. Maintaining current rates of pumping would result in peak production of corn and cattle around 2040-2050, followed by a decline in production. They also showed that to sustain agricultural production at the mid- 1990s level until after 2070 would require at least a 20% reduction in irrigation.

Climate change and groundwater irrigation

41. Aquifers are known to respond to climate fluctuation much more slowly than surface storage, and can therefore serve as an indispensable adaptation option for agriculture (GWP, 2012; OECD, 2013a; Wijnen et al., 2012). But increased demand with global warming may also result in increased groundwater use (Bovolo et al., 2009). Up until now climate related drivers have not affected groundwater as much as non-climate drivers (Kundzewicz et al., 2007). With changes in precipitation and increased evapotranspiration, however, climate change is bound to affect groundwater directly via a change in recharge and indirectly via increases in groundwater uses (Taylor et al., 2012). Coupled with a rise in sea water levels this additional use may lead to further salinity in groundwater (Green et al., 2011).

42. To a certain extent, the expected effects for agriculture can be observed in areas already subject to floods and droughts.[15] Regions facing drought that use groundwater in conjunction with surface water irrigation substitute the latter for the former, resulting in additional extraction and use. For instance, in Central California it was estimated that groundwater volume has been reduced forty-eight times faster during the drought of 2007-09 than before (Christian-Smith and Levy, 2011). At the same time, regions where agriculture relies primarily on groundwater will draw further on the resource.[16] Coastal regions may face a higher likelihood of seawater intrusion and resulting salinity, such as in the Netherlands (de Louw, 2013). Both types may also see changes in cropping patterns and activities over time. In contrast, regions facing prolonged flooding, may see groundwater floods, which would prevent most types of agriculture activities, and will only make fields usable for drainage, as observed for instance for the Chalk aquifer in Southern England (Marsh et al., 2013).

43. Given the lack of representative information on groundwater resources in many areas, and uncertainties related to climate change, simulating the effect of climate change on groundwater irrigation is not a trivial undertaking (Green et al., 2011). Two types of approaches have been used to provide elements of possible futures: foresight exercises and climate-water model simulations.

44. Expert-based elicitation has been compiled at the country level by OECD (2013e) in a broader study of water and climate change. In this exercise, countries were asked to define the main water risks they envisaged, list priority quantitative and qualitative risks and key areas of vulnerability. Table 4 provides a summary of responses that mention explicitly groundwater quantity-related risks.

15 See e.g. OECD (2013d) for more on floods and droughts.

16 In such cases, an important distinction is with respect to short run versus long run adaptation. Hornbeck and Keskin (2014) used an empirical analysis to show that users of the Ogallala aquifers who became less sensitive to drought early on, switched to water intensive crops in the long run, losing the advantage and regaining their sensitivity to drought.

Table 4. Identified concerns for groundwater resources under climate change in OECD countries

Country	Projected impacts	Primary concern	Key vulnerability
Austria	Reduction in the duration of snow cover, decreasing groundwater recharge	Decrease in groundwater recharge	
Chile	Retreat of glaciers will have impact on groundwater	Decrease in average recharge of groundwater; and groundwater salinization in coastal zones	
Czech Republic		Decrease in groundwater level	
Denmark	Reduced formation of groundwater in summer and an increased formation the rest of the year will affect irrigation. Intrusion of seawater in groundwater		Increased demand for groundwater resources.
Estonia	Increase in groundwater recharge, depending on the hydro-geological conditions of catchments.		
Finland	Longer dry period in summer in southern Finland will reduce groundwater discharge.		
Hungary			Overexploitation of groundwater resources
Japan	Groundwater salinization due to sea-level rise.		
Korea	Depletion of groundwater		
Luxemburg	Shift in the main recharge period of groundwater.		Groundwater recharge
Mexico	Salt water intrusion in groundwater		
Netherlands	Potential salinization of groundwater resources and decrease in levels of groundwater in the summer.		
New Zealand	Reduction in groundwater supplies and higher water demand in summer		
Portugal	Seawater intrusion into groundwater		
Slovenia		Decrease in annual groundwater recharge rate	
EU	Brackish and salt groundwater bodies will expand		Fresh water resources in Southern Europe, especially affecting agriculture

Source: OECD (2013e).

45. This table shows that OECD countries that do not use large volumes of groundwater still have significant concerns about climate change. The reduction of recharge, including the quantity and timing are considered an area of concern in countries like Austria, Luxemburg and Slovenia. Groundwater salinization is the other main concern, especially in countries with extensive coastal areas, like Chile, Japan, or Portugal. Agriculture is specifically mentioned as potentially affected in Denmark and southern Europe.

46. A number of published studies, not focusing on climate change, consistently report a likely increase in the use of groundwater for agriculture. Groundwater irrigation will continue to support agriculture intensification (FAO, 2003; Garrido et al., 2006). Economic drivers will increase agriculture use and pressure on aquifers especially in the Mediterranean region (Garrido and Iglesias, 2006). In Australia, the value and use of groundwater are also bound to increase, given demand projections, surface

water limitations, and the use of groundwater below recharge in multiple areas with the exception of fossil aquifers (Deloitte Access Economics, 2013).

47. There have been several simulations of climate change effects on groundwater, generally using recharge as a means to impact. Leterme and Maillants (2011) study the impact of climate change on groundwater and agriculture in Belgium. They find that by the year 2100 a 9% decrease in recharge is likely to occur in the Nete catchment overall. Land use adaptation options suggest that a conversion of the land to maize would increase groundwater recharge and therefore reduce climate sensitivity, while a conversion to forest would lead to the opposite result. Another study focuses on the Ogallala aquifer in the United States, finding that recharge would decrease by 20% (Schaible and Aillery, 2012). Yet, depending on the scenario, and the portion of the aquifer, recharge could see an increase or decrease, and it is difficult to reach any significant conclusion (Crosbie et al., 2013).

48. With this overview of groundwater agriculture use and trends, the following section shifts towards an analysis of the nature and heterogeneity of groundwater irrigation systems.

Characterising agriculture groundwater systems in OECD countries

49. As noted above, there is significant variability in the types of aquifers and related agricultural systems, and consequently in their use and management practices. The objective of this section is to synthesize this diversity, by proposing a characterisation of groundwater irrigation systems in a tractable and consistent manner in OECD countries, for use when considering management and policy options. This exercise therefore aims to help avoid either a misleading over-generalisation of challenges and responses (see, e.g. "all groundwater should be managed the same way") or an overstatement of the diversity of cases and their importance in determining potential responses (see, e.g. "each aquifer requires its own unique and nonreplicable management plan").

50. More specifically, this section reviews relevant typologies in the literature, discusses what criteria stand out from others and could be used to group similar types of constraints, and use these two steps to move towards a characterisation for groundwater irrigation systems in OECD countries.

Existing aquifer typologies

51. There have been multiple efforts to categorise aquifer systems, accounting for dimensions related to hydrogeology, geography, as well social, institutional and economic considerations. Each of these efforts attempted to address the same dilemma of trying to provide a representative framework of a large diversity of aquifers. As late agriculture economist S. von Cyriacy-Wantrup wrote: "*In the economics of ground water, special caution is indicated when the attempt is made to generalize. On the other hand, generalizing is a necessary part of the tools and the objectives of research*" (Snyder, 1955). This section rapidly reviews some of the main efforts undertaken in this area, from international classifications of aquifer systems to socio-economic typologies of groundwater irrigated agriculture.

52. The first characteristics of interest relate to the nature and physical properties of a given aquifer.[17] Five main types of aquifer can be found (Box 2): sand and gravel, sandstone, karst, volcanic and basement aquifers (Margat and van der Gun, 2013). Each of these types is associated with specific physical properties, such as porosity, conductivity and thickness that determine the flow and storage aquifers can allow. The two first types include the most conducive agriculture irrigation systems, and some of the most fertile land. But other types of aquifer are also significantly used for irrigation.

[17] Box 1 provides some basic properties common to all aquifers, this section reviews the main differences they present.

Box 2. Five main types of aquifers

- *Sand and gravel aquifers* include extensive largely used continuous aquifers (Ogallala, Central Valley California) and local alluvial valley aquifer, that are present in virtually all streams; they are the most common and easily accessible, often unconfined with relatively shallow water tables.
- *Sandstone aquifers* are consolidated sand structures, they also include major aquifers; they have a lower transmissivity than sand and gravels. OECD examples include the Great Artesian Basin in Australia and the Northern Great Plain in North America, but also some smaller shallow aquifers, such as the Coastal aquifer in Israel.
- *Karst aquifers* are discontinuous complex structures, formed of cavities between different rocks, they are outlets for sources, have a good flow, but heterogeneous storage capacity, and can be largely recharged by rainfall. Examples include the Chalk Aquifer in the United Kingdom and France, multiple aquifers in Greece, the Midya aquifer in Turkey and the Yucatan Aquifer in Mexico.
- *Volcanic aquifers* are largely fragmented aquifers, often formed in fissures or porous volcanic structures. OECD examples include the Sierra Madre Occidental in Mexico, the Canary Islands in Spain, part of the Andes in Chile and multiple aquifers in volcanic islands (Iceland, Japan).
- *Basement aquifers* are based on crystalline and metamorphic rocks, include different structures that are not always exploitable. Deeper parts include discontinuous groundwater pockets, with limited storage and good transmission, while shallow structures can have a better storage but less transmissivity. Examples include most of Scandinavia, and part of Australia.

Source: Margat and van der Gun (2013), Bar-Or and Matzner (2010).

53. Still, these characteristics have to be associated with the scope and extent of aquifers to determine flows and storage potential: the degree of confinement, depth and volume all matter in this regard (Box 1). Multiple organizations have worked to combine such geological and geographical considerations into a simplified globally applicable classification of hydrogeological settings (WHYMAP, 2004). Their classification includes three categories: a) major aquifers, b) areas with complex hydrogeological structures, and c) areas with only local and shallow aquifers. Their characteristics and the correspondence with the above presented geological typology of aquifers are presented on Table 5. Major aquifers (a) tend to have a high storage to transmissivity ratio, complex aquifer structures (b) have discontinuous water reservoirs with variable ratios, and shallow aquifers (c) include structures with much lower ratios overall. These three major classes are now used as a standard for international maps of groundwater resources (e.g. see Figure 8).

Table 5. Three classes of aquifers

Hydrogeological setting	Types of aquifers	Physical characteristics	Agriculture use implications	Examples in OECD countries
Major aquifers	Mostly sand and gravel and sandstones aquifers	Significant storage, low flows	Potential for Intensive irrigation use	See Table 2
Complex hydrogeological structures	Mixed, includes karst and volcanic aquifers, and some basement aquifers	Shallow or deep, variable stock to flow ratio	Localized productive irrigation potential uses	Po valley region in Italy, Spain's main aquifers, Turkey's aquifers
Areas with local and shallow aquifers	Alluvial formations (sand and gravel), sometimes on top of basement aquifers	Limited and localized resources, higher flow than storage	Limited scope potential, as complement with surface water	Central Europe

Source: Derived from WHYMAP (2004) and Margat and van der Gun (2013).

54. A third approach has been undertaken to group similar types of aquifer systems by region. The International Groundwater Resources Assessment Centre (IGRAC) has defined 36 global groundwater regions divided into 217 groundwater provinces (Margat and van der Gun, 2013). These divisions were developed focusing on the predominant characteristics of groundwater systems in continental regions. Four main categories of groundwater regions: *basement regions* (noted B), *sedimentary basins* (S), *high relief folded mountains regions* (M), and *volcanic regions* (V). These categories largely match the five aquifer types presented in Box 2, with the two first types under the sedimentary category (S), karst aquifers under the mountain region category (M). Table 10 in the appendix provides basic information about the sixteen groundwater regions that cover OECD countries. Most productive agricultural regions that use groundwater belong to the five regions of the (S) category (two in North America, one in Europe, one in the Middle East and one in Oceania) or to the six M categories in the set (two in North America, one in Europe, two in Asia, and one in South America).

55. Building on these categorisations, social scientists have moved towards a differentiation that takes into perspective the degree and type of human exploitation or the potential thereof. More specifically, three global typologies of groundwater use have been described and referred to in the agriculture literature, developed by researchers at International Water Management Institute (IWMI), the World Bank's GW-Mate project, and the FAO, respectively. Table 6 provides a comparison of the main criteria and classes as well as where OECD countries would stand. Detailed information on each classification system is shown in the appendix (Tables 11, 12, and 13).

56. First, Shah et al. (2007) use multiple agricultural, geographical and economic variables as indicators to define four categories of countries, depending on the nature of the predominant agricultural systems and its relationship with groundwater. The four categories are used to determine the dynamic impact of intensive agricultural use. Secondly, Foster et al. (2009) separate different conditions of aquifer exploitations, as found in various developing countries, to derive a list of three main types and nine more specific types of conditions. Their typology does not explicitly focus on agriculture use, but given the overall focus on development, clearly does address different types of utilisation of groundwater and their consequences. Lastly, Siebert et al. (2010) reviews the role of groundwater irrigation under four conditions, depending on the type of climate and ability to withdraw groundwater from the aquifer.

Table 6. Comparing the main socio-economic typologies

	Main considerations	Key criteria or variables used	Types	Class of OECD countries
Shah et al. (2007)	Geographic, economic, and social	Groundwater irrigated area, climate, water resource, population, agriculture organisation, drivers of groundwater irrigation, economic significance of groundwater irrigation	1. Arid agricultural systems; 2. Industrial agricultural systems; 3. Smallholder farming systems; 4.Groundwater supported extensive pastoralism	Type 2 for all countries except Turkey (Type 1).
Foster et al. (2009)	Risk of aquifer degradation, likelihood of conflict, and level of knowledge	In addition to those, exploitation status, quality Issue, and degree of depletion	(1) At risk of extensive quasi irreversible aquifer degradation	Not clear, depending on situation, some aquifers under (1), some others under (3).
Siebert et al. (2010)	Favourability of climatic and groundwater withdrawal conditions	Groundwater recharge(low or high) transmissivity and storage of aquifers (both low or high)	a) Irrigation from recharge or non-renewable deep wells, b) surface water irrigation, c) irrigation from renewable groundwater, d) surface water irrigation	Four categories are likely to be found in OECD countries: a) major aquifers in arid areas b) South West USA, c) European lowlands, d) Western Canada

Source: Author, based on listed references and typologies, as presented in details in Tables 11, 12, and 13 in the Annex.

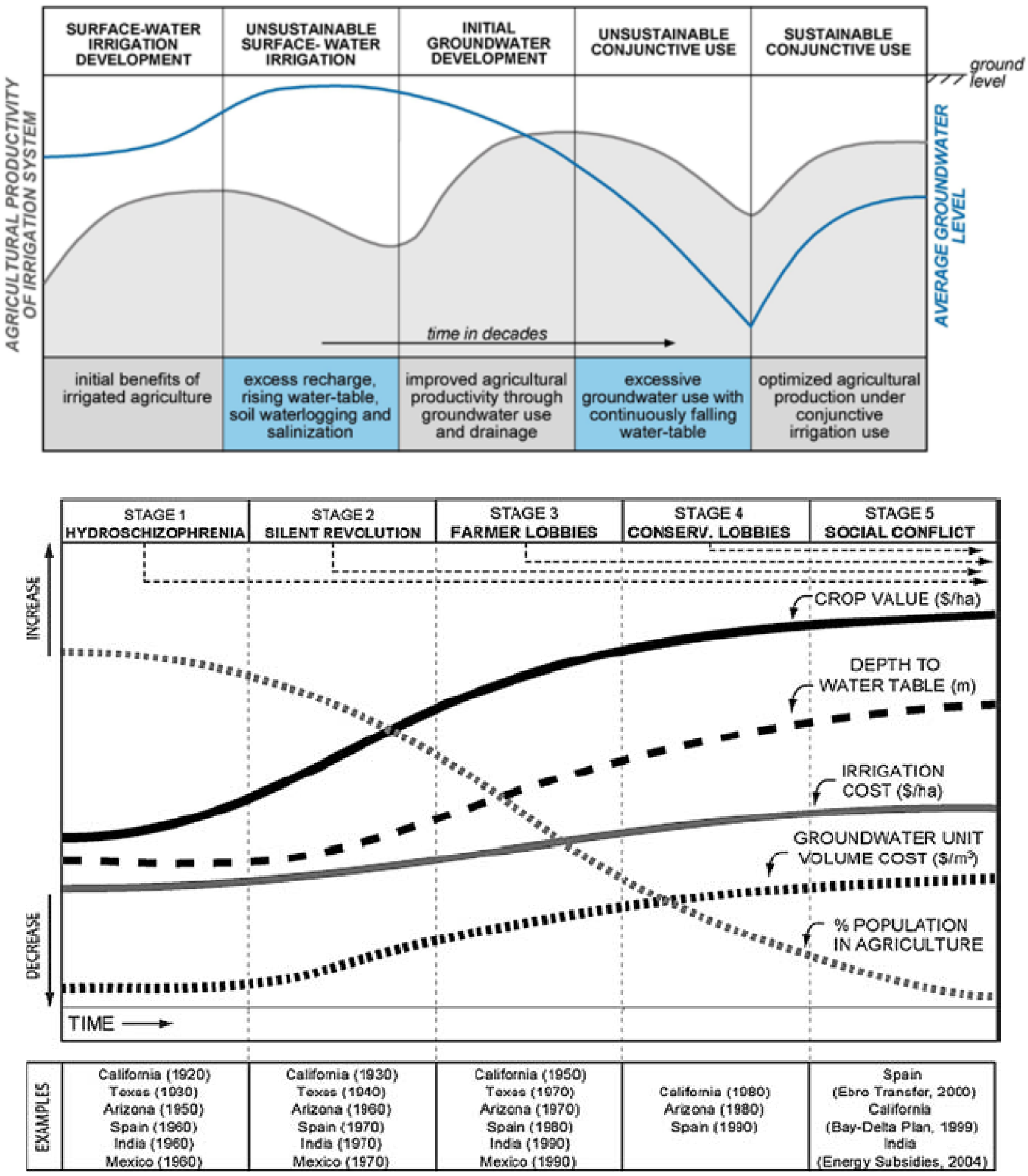
57. The three systems provide a list of dimensions and variables that are worth considering, but they also were developed to fit a larger set of agro-economic conditions than those seen in most OECD countries (e.g. including small farms in South and East Asia or Sub-Saharan Africa). As shown in the last column of Table 6, they may not be well adapted to OECD countries' groundwater irrigation systems. The irrigation typology of Siebert et al. (2010) may be the only one able to cover a large number of groundwater irrigation systems, even if some aquifers used for irrigation may not have a low transmission *and* low storage or a high transmission *and* high storage.

58. Lastly, two dynamic characterisations of groundwater systems provide an interesting alternative. Instead of static characteristics, they are founded on stages in the evolution of groundwater systems' exploitation (Figure 11). The first one relates groundwater to surface water use for irrigation in circumstances where both are available (GWP, 2012). Surface water is first predominant, and becomes unsustainable. Groundwater is then exploited, with increased popularity until a peak, and in the last stage both are used in a sustainable conjunctive use system.[18] The second typology focuses on the political economic evolution of the system (Garrido et al., 2005). Five economic variables and five main political economic stages are considered, each related to a particular era in groundwater use in specific countries. Stage 1 is called "hydroschizophrenia", it represents the discovery stage, in which groundwater is ignored in the political discourse, with a focus on surface water infrastructure and issues. Stage 2 represents the rapid and "silent" development of groundwater irrigation. Stage 3 and 4 stand for increased political pressure from farmers and conservationists, and the last stage relates to social conflict.

18 Conjunctive use is the term used for the joint management of surface and groundwater.

Figure 11. Evolution of groundwater irrigated agriculture: two perspectives

Top panel: surface and groundwater uses over time in dual water systems, Bottom panel: socio-economic stages in the use of groundwater systems



Source: Top: GWP (2012), Bottom: Garrido et al. (2005).

Main criteria of importance for OECD agriculture

59. Drawing from these five socio-economic typologies, but looking more specifically at groundwater irrigated agriculture in OECD countries, a characterisation can be proposed. The first step in the process is to define which factors- including from those presented above- matter when describing agriculture groundwater systems in OECD countries and that are of relevance for assessing groundwater management and policy options.

60. One way to proceed is to ask where groundwater is used for agriculture in OECD countries. As Shah (2009) points out (Box 3), climate, resources, and agriculture activities are all critical. The relationship between surface and groundwater also clearly matters, as noted in Siebert et al. (2010)'s typology. To put it simply, the following four conditions are found to be necessary to the rational intensive use of groundwater for irrigated agriculture:[19] a) insufficient or unsteady precipitations, b) inadequate or insufficient access surface water supply, c) accessible, available, and usable groundwater resources, and d) continued profitability of groundwater use for irrigation especially compared to other competing uses.

Box 3. Four working rules of groundwater irrigation

In a chapter dedicated to provide a global overview of groundwater use in agriculture Shah (2008) identified the following four working rules to the intensive use of groundwater for irrigation:

"1. Intensive groundwater irrigation would emerge primarily in arid and semiarid areas that satisfy other preconditions for productive agriculture but do not have enough rainfall or surface water (such as the US great plains, Spain, or Central Mexico).

2. It would be uncommon in humid areas with abundant soil moisture and surface water (South America, Central Africa).

3. It would be uncommon in regions with poor aquifers that are costly to develop and offer low, uncertain yields often of poor quality water (Southern Africa).

4. It would decline on its own in a region as depleted aquifers become prohibitively costly to tap for irrigation or yield poor quality water (parts of US West, Saudi Arabia)."

Source : Shah (2009).

61. The necessary nature of these conditions is easy to demonstrate: absence of one of these conditions suffice to eliminate the rational for intensive use of groundwater irrigation. Large rain endowment during growing seasons eliminates the need to look for alternative resources. Steady, sufficient and efficient access to surface water refrains from investment in finding and accessing groundwater. The lack of access to aquifers, insufficient or unusable groundwater resources clearly impede on its use. And the rapid degradation of profitability of groundwater aquifers, or the growing competition it faces from other sectors may prevent investment into groundwater use.

62. Each of these qualitative conditions can be turned into variables to characterise groundwater resources and aquifers. Once again, climate and groundwater resources matter, as do the degree of use and relationship with surface waters. The relative comparative advantage of groundwater irrigation on surface

19 We exclude productive rainfed agriculture areas, where irrigation itself is not economically justified (e.g. large parts of Canada and Northern Europe).

irrigation will depend on a number of factors. Box 4 discusses some of the main elements considering the interface and differences between surface and groundwater irrigation systems in general. Among the exogenous factors for farmers, the comparative cost of access to one or both options matter.

Box 4. Surface and groundwater irrigation

Surface water overlaps with groundwater irrigation in multiple countries (e.g. in Japan see FAO, 1999), especially as buffer storage under drought (Green et al., 2011, ICID, 2010). But this is not always the case; in the United States, less than 20% of the farms and 25% of irrigated area have access to multiple water sources (OECD, 2009c). Large parts of northern Mexico does not have access to surface water and therefore uses groundwater as sole source of irrigation (Scott et al., 2010).

There are multiple physical, economic, and institutional differences between the two types of irrigation systems, that condition their use as substitute or complements.

- *Physical access* to surface versus groundwater is a significant factor for irrigation. Surface water irrigation requires steady access to watercourses overtime, which will depend on the state and maintenance of local and river basin infrastructure, and on seasonal patterns in rainfall. Groundwater on the other hand is less dependent on both but requires in most cases individual investment into well-drilling and maintenance.

- The *structure of the cost of access* to groundwater versus surface water may differ for users. For groundwater a fixed cost is required, and variable cost may depend on the evolution of resources and energy sources. Both are often individually born by farmers who act as entrepreneurs (Garrido et al., 2006). For surface water, the cost can be largely born by external public agencies, and variable costs depend on charges, which may be subject to subsidies (Garrido et al., 2006).

- While both can be considered common pool resources, *distribution and equity in access differ*. Surface water is directly and visibly dependent on river basin cooperation mechanisms, and some users have advantage over others (upstream users). Groundwater resources may also necessitate cooperation among users, but water is often available to multiple actors, without visible control or cross-monitoring (Wijnen et al., 2012).

- *Legal access and entitlements* also matter; while both may be subject to water rights, surface water may be managed under specific allocation systems that differ greatly from the institutional and legal frameworks that are used for groundwater. The use of Rule of Capture, for instance, whereby farmers have the right to access and use any groundwater resource under their land, is still predominant in certain parts of the United States (e.g. Peck, 2007). Under such rule, any land-owner is theoretically free to exploit resources on its own without restriction.

Building on these characteristics, wherever possible, conjunctive use of surface and groundwater can provide flexibility for farmers (Kemper, 2007), increase overall productivity (Giordano, 2009), and lower risks associated with stochastic water supply and climate volatility (Schoengold and Zilberman, 2007; Taylor et al., 2012),

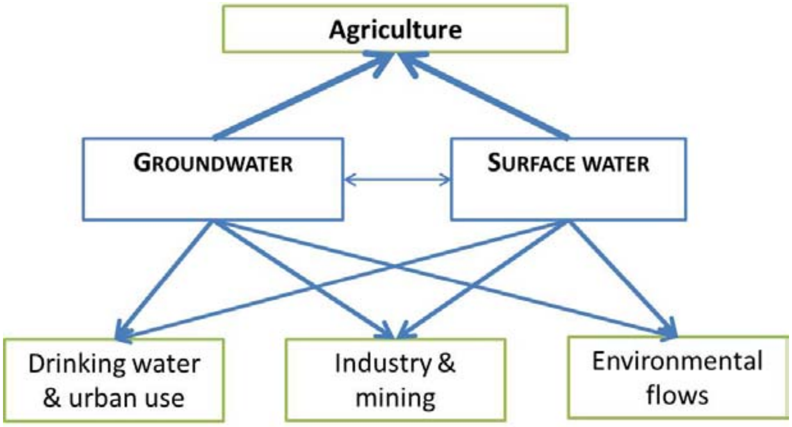
Source: Authors based on cited sources.

63. Competing uses to agriculture also matter for the state and evolution of groundwater resources. As shown schematically in Figure 12, groundwater and surface water can both supply four main sources of demand: agriculture, urban (water sanitation) and drinking water, industry and mining and environmental flows. While each of the two sources of water can be used for all purposes, they rarely are used in conjunction for exactly the same type of demand. Drinking and urban water are often sourced from groundwater, while industry and agriculture more often rely on surface water.[20] In some cases competing

[20] In the European Union, for instance groundwater represents 70% of domestic water use and only 20% of irrigation water (OECD, 2012b).

uses can contribute to groundwater stress. For instance, recently developed activities in the energy sector, using hydraulic fracking, has been found to be using significant amount of groundwater, especially in water stressed agricultural irrigation areas in the United States (Ceres, 2014).

Figure 12. Groundwater and surface water uses



Source: Author.

64. Primary variables and associated elements of groundwater irrigation systems can be added to these four conditions. In particular, the following factors seem to stand out from the reviewed typologies: recharge and renewability, storability and transmissivity of the aquifer, stage in the use and degree of depletion. The number of users per aquifer also may matter. Indeed, taking two aquifer systems identical in terms of the other variables, but one with three users and the other with three thousand, will lead to radically different types of issues and responses (Giordano, 2009).

Proposed characterisation

65. Four guiding principles may help developing a usable characterisation: i) the need to ensure a comprehensive coverage, as much as possible representative of groundwater systems in OECD countries, ii) the absence of major gaps, for which no case could be found, iii) the absence of main overlaps across criteria, that would have the fulfilling of one criterion always imply another one, and iv) well-defined and workable boundaries that respond to the objective.

66. This exercise focuses primarily on identifying exogenous factors that matter when looking at economics, management and policy surrounding the use of groundwater for agriculture. In other words, the goal is not to classify different management or policy action, but rather to determine what variables intrinsic to the system could be used to distinguish the consequences of such action for different groundwater systems.

67. Using the previously presented four necessary conditions as main factors and the discussed primary and secondary variables, a characterisation of groundwater systems is proposed in Table 7. The first three main factors are essentially covering state variables describing the context of any groundwater system, conditioning its potential for irrigation. The last factor covers exogenous variables related to trends in demand and overall past use, which may affect the present and future potential for groundwater irrigation. These variables are set to act as a "proxy" for the relative profitability potential of the system.

Table 7. Proposed characterisation of agriculture groundwater irrigation systems

Main factors	Primary variables of interest	Secondary variables	Typical responses
Agro-climatic conditions	Precipitation in growing season	Cropping systems	Arid, semi-arid or humid regions
Access to surface water irrigation systems	Availability and relative cost of surface water	State of surface water Infrastructures, location in water basins.	Available and easily accessible surface water or unavailability of surface water
Availability of accessible and usable groundwater resources	Transmissivity and storage capacity; State of resource and recharge; Topography and type of landscape; Quality concerns	Geological aquifer type, hydrogeological and geographic setting, depth and degree of confinement; withdrawal rate; proximity to rivers, lake or oceans.	Accessible aquifer with high storage low transmissivity and recharge rate Accessible groundwater resources from a shallow aquifer with low reserve in coastal areas. Limited accessible resources with a deep confined aquifer in a complex hydrogeological structure in a mountainous context. Low quality coastal aquifer (brackish water).
Trend in use and profitability of groundwater irrigation relative to other uses	Cost of access to groundwater Scope of irrigation use Intensity of irrigation use Trend in competing uses	Fixed and exogenous variable costs N users and irrigation area Overall trend in use and GDS; Stage of exploitation and stress Population growth, trend in water demand	Declining groundwater irrigation use due to depleting stocks Continued groundwater use with growing outside demand Increased use and expansion for irrigation.

Source: Author.

68. While specific cases are not presented, adopting this framework can provide a general overview of predominant groundwater systems in OECD countries. Considering the main factors, a large number of intensively exploited irrigation groundwater systems in OECD countries (USA, Mexico, Southern Europe, Australia) tend to be in semi-arid or arid areas, some with surface water (conjunctive use) others not, with abundant and accessible but increasingly stressed groundwater resources. At the same time, looking at primary variables can help understand singularities across these aquifers, including which systems are at an advanced stage of exploitation and which are not, their degree of depletion, changes in competing uses and options they have to use more surface water or not. In contrast, some less exposed but still significant groundwater systems in OECD countries (e.g. in parts of central and northern Europe, Japan, Korea, Canada and Chile) may be located in relatively more humid regions, with abundant but parcelled groundwater resources used in conjunction with surface water, where agriculture may not always be the primary using sector, and with localised and temporary stresses. But the number of users, demand drivers, cropping systems and groundwater availability may vary significantly from one to another.

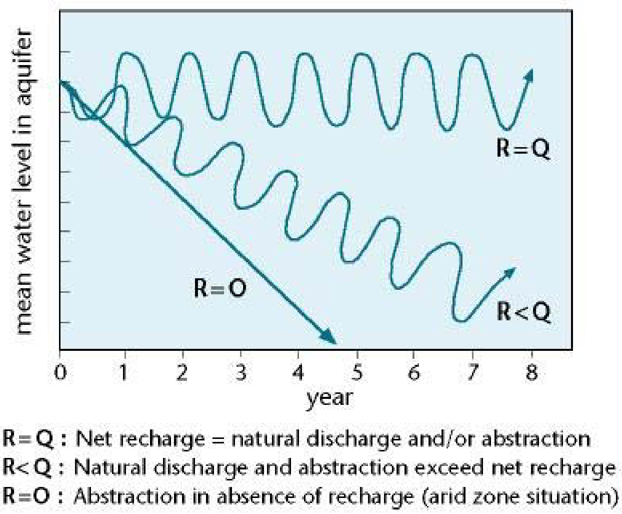
69. The purpose of the characterisation is to provide elements of differentiation for the economic and policy sections of the reports. First steps may be to conceptualise the importance of the factors in groundwater use, all else being equal. Groundwater current and potential use clearly depends on the four main factors, but assessing how much they matter would be a useful exercise. In general, groundwater irrigation systems that are most at risk of overdraft, include those: a) with arid or semi-arid climates and water intensive crops, b) where surface water is unsteady, unavailable or insufficient, c) that do have a significant access to groundwater resources, with potentially limited recharge, d) that are continuing to experience an increase in use either in scope (irrigation or outside) or in intensity.

70. The proposed system could also be used to assess the effects of changes in the main factors. First and foremost, climate change may affect surface water and as such the likely use of groundwater in multiple areas (e.g. Famiglietti et al., 2011), even if it will not always result in significant short term changes in the state of resources. But a change in surface water availability, due to infrastructure development or institutional change is also possible, and may affect the use of resources. An external shock on the groundwater system itself (earthquake), would clearly affect potential use. And a rapid increase in the scope and use of groundwater, due to competitive demand for instance, would clearly impact the state and potential of the resource.

Key constraints and challenges for groundwater use in agriculture

71. To complement the characterisation, this section looks at the main challenges related to the use of groundwater irrigation. Three types of evolutions can be seen in exploited groundwater resources: steady use, following recharge, progressive overdraft and mining. The consequences of such strategies on water tables are shown in Figure 13. While these are easy to define and harder to measure, the question of which strategy may be best is subject to discussion.

Figure 13. Patterns of groundwater abstraction



Source: BGS (2009).

72. Just like the definition of "renewable" may vary among practitioners (e.g. see Box 1), the term "overexploitation" is also employed in different settings, depending on the definition of what constitutes a normal or acceptable exploitation path. The literature often refers to sustainable yield (or no overdraft) as the reference for acceptable exploitation, but many authors argue that this definition does not make sense economically. Indeed, mining groundwater in non-renewable aquifers to generate capital and prepare the future can be better than keeping the stock as such (GWP, 2013). Overdrafting aquifers to some extent, may lead to tremendous gains for farmers and communities, later increasing their capacity to adapt to future water constraints. As an alternative, Llamas and Garrido (2007) suggest the following definition: "*an aquifer is overexploited when the economic, social and environmental costs that derive from a certain level of groundwater abstraction are greater than its benefits*." This would imply considering a system in a dynamic cost-benefit analysis, which has some merit, but also faces challenges. In practice, water management bodies go beyond a discrete description of exploitation levels to define quantitative reference

states to which to compare groundwater levels (EEA, 2013). Some countries even define multiple water table threshold levels for intervention (Séguin, 2009).

73. The underlying question around these concepts is at what point groundwater use intensity does lead to unwanted consequences. One way to frame the problem is to focus on externalities related to irrigation use of groundwater. Two main types of externalities operate in groundwater irrigation systems: extraction cost externalities and environmental externalities (Esteban and Dinar, 2012). Table 8 presents these effects in more details according to their degree of reversibility.

Table 8. Reversible and irreversible consequences of intensive groundwater abstraction

Type	Consequences of intensive abstraction	Factors affecting susceptibility
Reversible	Pumping lifts/costs increase Borehole yield reduction Springflow/river baseflow reduction	Aquifer response characteristic Drawdown below productive horizon Aquifer storage characteristics
Reversible or irreversible	Phreatophytic vegetative stress (natural and agricultural) Ingress of polluted water (from perched aquifer or river)	Depth to groundwater table Proximity of polluted water
Irreversible	Saline water intrusion Aquifer compaction/transmissivity reduction Land subsidence and related impacts	Proximity of saline water Aquifer compressibility Vertical compressibility of overlying/inter-bedded aquitards

Source: Foster et al. (2013).

74. The first type of externalities involves increasing cost for everyone, counterproductive competition among users, and potentially with non-agricultural users. Even if reversible, such pumping can result in increased costs and lower volumes for all (Pfeiffer and Lin, 2013). Its extent clearly depends on the nature of aquifers, and may depend on the level of knowledge of competing users on the state of the resource (Saak and Peterson, 2007). In the proposed characterisation, pumping externalities are more problematic in groundwater irrigation systems that have an arid climate, limited surface water access, accessible resources in continuous large area aquifers with limited flows and especially storage but multiple users competing against each other.

75. In the case of environmental externalities, multiple consequences can arise, some reversible, and other irreversible, some directly affecting agriculture activities while others only directly affecting the environment. The first listed effect on Table 8 relates to the widely observed occurrence of stream depletion, in which pumping close to waterways affects surface water level in streams, rivers and lakes. This phenomenon has led to intra- and inter-state conflicts in the United States (Kuwayama and Brozović, 2013), and can have implications on irrigation systems, reducing options for farmers. The main type of affected groundwater irrigation systems are those with conjunctive use, for which groundwater is in connection and in proximity with surface water bodies. Two additional reversible or irreversible effects are listed on Table 8. Vegetative stress can affect all plants, while pollution ingression may depend on other activities, and will not always have visible consequences on crops, depending on concentration and type, but can affect drinking water sources.

76. Lastly, three types of irreversible consequences are environmental externalities that can also create tremendous long term problems for agriculture: aquifer compaction, salinization, and land subsidence. Of these three, compaction is a geological phenomenon that may result in the progressive or complete elimination of flows from aquifers. The effect on farmers may be similar to that of aggressive depletion of the resource. De facto, eliminating aquifers is comparable to eliminating the possibility of using any groundwater. But the extent of this effect and its relationship with agriculture does not appear to be largely discussed in the literature. The next subsections therefore focus on the two other irreversible

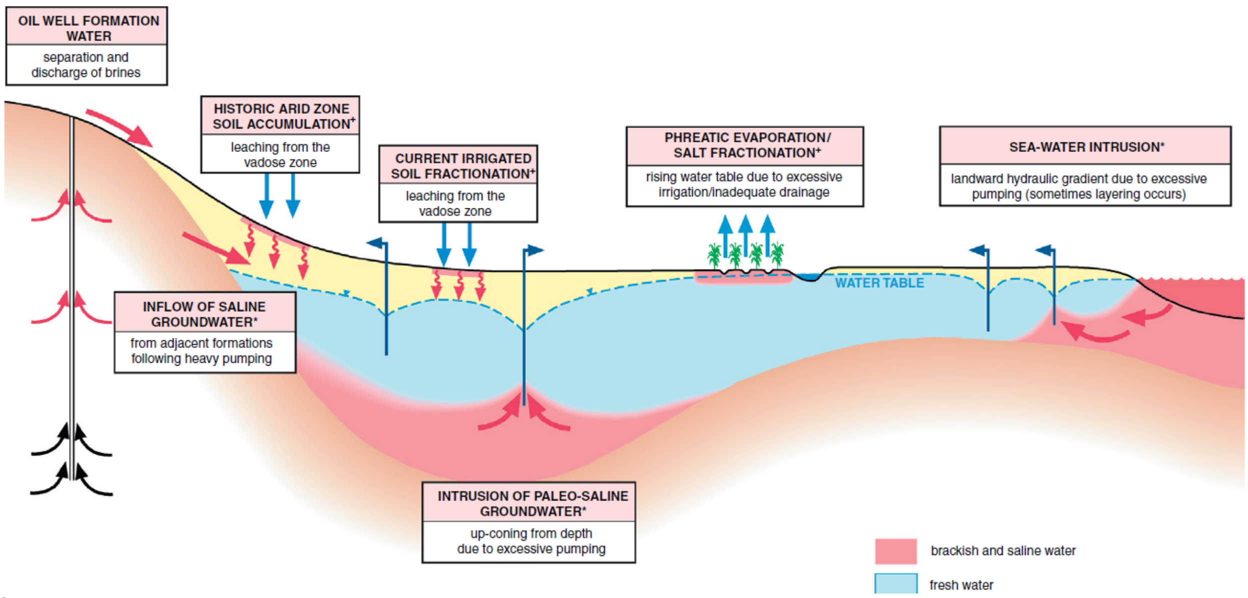
consequences, which have proven to have significant environmental and agricultural impacts: salinization and land subsidence.

Groundwater salinity

77. Salinity[21] is one of the most important and growing constraints for irrigated agriculture. It may affect up to 20% of irrigated areas, and threatens nearly half of all irrigated areas in the long term (Le Kama and Tomini, 2012). 1.5 million hectares may be taken out of production as a result of land salinity every year and the total global costs for producers may exceed USD 11 billion/year (Schoengold and Zilberman, 2006).

78. Even if a large share of saline water intrusion in aquifers is due to the use of groundwater for irrigation, it is not the only driving factor (Balderacchi et al., 2012). Figure 14 provides a synthetic representation of the main sources of groundwater salinity. Of the identified seven sources, four are directly caused by pumping: inflow of saline groundwater following heavy pumping (cone), deep intrusion of saline groundwater,[22] phreatic evaporation under intensive (surface water) irrigation in the absence of drainage (water logging), and sea water intrusion in coastal areas. A fifth category (soil fractionation) is related to irrigation of the soil, but not necessarily resulting from groundwater pumping.

Figure 14. Main sources of groundwater salinity



Source: Foster et al. (2013).

79. Salinization can be disastrous for agricultural activities. The physiological process is relatively straightforward: when saline water is used by plants, water is used by plants and salt are left in the root zone, therefore rapidly rendering soils saline, which increasingly becomes less permeable to water (Le Kama and Tomini, 2012). Plants die rapidly and salt crystals remain embedded in the soil. In the absence of remedies, only salt tolerant crops can survive. Removing salt in soil can be done via proper drainage, but is rarely completely eliminated, and can be highly onerous (Foster et al., 2013). Prevention, using artificial

21 Salinity can be defined based on the total concentration of dissolved solid (TDS); water is called brackish if TDS is above 1000 mg/L, and defined as saline over 10 000mg/L (Margat and van der Gun, 2013).

22 As noted in Table 1, about 60% of total groundwater reserves are brackish or saline water.

groundwater recharge can work, as shown in Tunisia (Garrido and Iglesias, 2006) or using barriers as in Israel (Margat and van der Gut, 2013). The use of drip irrigation can also help slow the process (Cooley et al., 2009).[23]

80. A number of OECD countries are especially concerned with seawater intrusion in coastal areas (such as Italy and Greece, see EACSAC, 2010a; EASAC, 2010b). In such situation, the challenge is not only to avoid intensive pumping but to keep a sufficiently high level of freshwater in aquifers, to slow the penetration of salt water. In the central coast of California, a highly productive area for produce, freshwater sources are not only sought as an alternative supply to groundwater use but also to be used as groundwater recharge to sustain aquifers in the future (Levy and Christian-Smith, 2011). In some case, as in the Nueva lagoon region in Spain, sea water intrusion can also filter into wetlands, affecting plants and other species in the local ecosystems (Amores et al., 2012). In other cases, with low altitude surface coastal areas, like in the Netherlands, sea intrusion in groundwater can result in seepage in surface water, affecting lakes, rivers, and complete regional water systems (de Louw, 2013).

81. Following the proposed characterisation, the most affected systems are those that are most inclined to use groundwater significantly (as defined above), but also those in proximity with salted water resources. This includes groundwater systems in coastal areas, with limited supply in fresh surface water, and a relatively high degree of exploitation, such as the Hermosillo coastal aquifer in Mexico (Custodio, 2003), and multiple areas in Greece (EASAC, 2010b). Other areas concerned are those where groundwater levels are in proximity with surface water (lowland region of Europe see Table 10 in Annex). And areas in proximity with underground saline water, including shallow alluvial aquifers such as those in New Zealand and paleo-channels in Western Australia are also subject to saline constraints (Magat and van der Gun, 2013).

82. Salinity in such areas will furthermore likely increase with climate change (Green et al., 2011). As seen in the Mexilhoeira Grande-Portimão aquifer in Portugal, sea water intrusion can be especially intensive during dry periods (EASAC, 2010c).

Land subsidence

83. Land subsidence is one of the most important impacts of intensive groundwater abstraction. Drawing water in aquifers made of unconsolidated and porous geological structures, including sedimentary complexes, can result in significant compaction of aquifers that in some case results in the sinking elevation of the land surface (Margat and van der Gun, 2013). Multiple impacts can then be observed from the deterioration of infrastructure, buildings, or even pumping systems themselves, to the displacement of water courses and energy networks, to the destruction of trees, erosion and so on. Total damages can be very large; in California and Texas, they were estimated to exceed USD 100 million/year (OECD, 2012a).

84. Land subsidence takes place in multiple contexts, many of which are not related to agriculture. Box 5 provides some of the well-known reported cases in OECD countries. Japan's major urban areas have known significant land subsidence episodes, but these events were related to intensive pumping for urban water use, not agriculture (Taniguchi et al., 2008). Similarly, land subsidence has impacted the Po delta in Italy, but it was mostly related to urban and industrial development (Teatini et al., 2006). Yet multiple examples in high exploitation areas are resulting directly from groundwater irrigation. For instance, agriculture irrigation contributed to the large subsidence observed in the Guanajuato State in Mexico (Custodio, 2003) and the case of the Central valley of California in the United States (FAO, 2011).

23 There are also breeding programs to render traditional crops salt tolerant in a number of countries, but the results are still not satisfying.

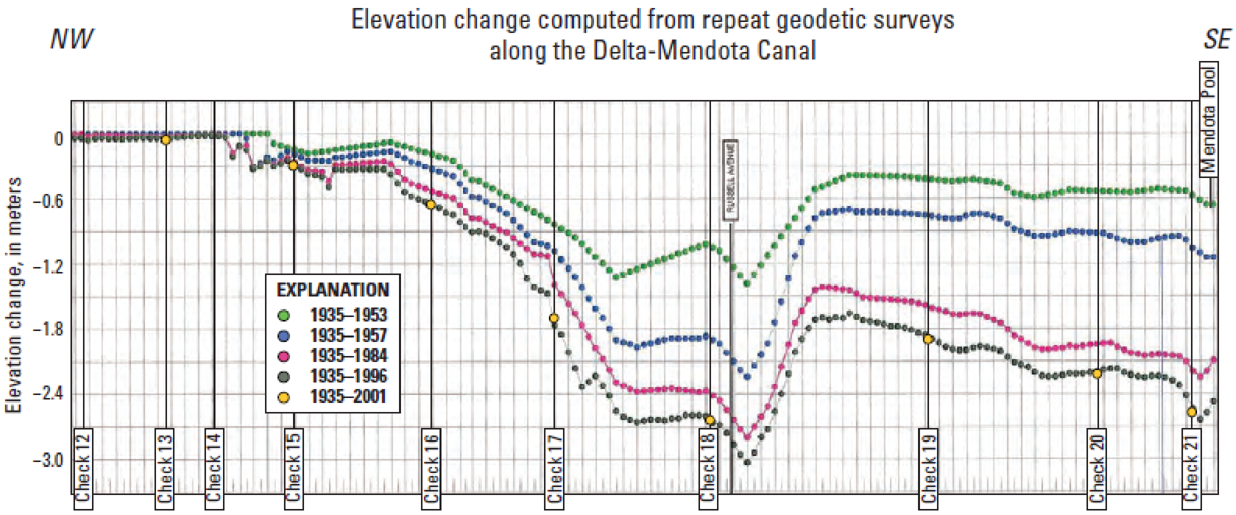
Box 5. Groundwater withdrawal induced land subsidence in OECD countries

UNESCO (1984) inventoried international cases of land subsidence related to groundwater exploitation. They found 42 cases, mainly located in urban agglomerations, perhaps because of better measurement. More recent efforts have included dozens of new cases. In particular, notable examples in OECD countries include:

- Milan (subsidence of 0.2 m from 1952 to 1972); Venice (more than 0.2 m since the 1930s) and the Po Delta, (more than 3 m during the 1950s) in Italy.
- Mexico City (since the 1920s up to 0.4 m per year in the Centre, up to 10 m). Mexico City (300 mm/year during 2004–2006), Toluca Valley (90 mm/year during 2003–2008) in Mexico.
- Denver, Houston, Las Vegas, San Francisco, Tucson; up to 2–9 m of subsidence in several cities in California, the San Joaquin valley. Coachella Valley, California (70 mm/year during 2003–2009); the Bolsón del Hueco basin around El Paso in Texas (0.3 m of subsidence since the 1950s), In the United States.
- Tokyo (starting in 1910; subsidence up to 4 m; land surface fell to 1 m below sea level), Osaka (up to 2.5 m) the Sagamigawa alluvial plain in Japan (up to 0.32m during 1975–1995) and another 62 cases reported in 1998 in Japan.

Source: Margat and van der Gun (2013), Famiglietti et al. (2011), UNESCO (1984).

Figure 15. Evidence of gradual land subsidence in California



Source: Sneed et al. (2013).

85. Figure 15 shows the evolution of land levels in a specific area of California's central valley. In this example, land has decreased by up to 2 meters during a seventy year span, but it was estimated to be above 8.5 meters in other areas (Sneed et al., 2013). The pattern and rhythm of land subsidence during this period has followed the evolution of water use, with rapid depletion early on, then slowing down with the development of surface water irrigation infrastructure, and then again re-acceleration of the process during the more recent period of droughts (Sneed et al., 2013).

86. Consequences for agriculture may not always be as directly visible as those in the case of salinity, but long term impact can threaten any agriculture activity on the land, damage ecosystems, discourage investments, and affect rural communities. It can also result in sea level intrusion and associated flooding, result in water logging and salinity including in low lying delta regions (Custodio, 2003; de Louw, 2012). Prevention of such events, just like salinity, involves better management of groundwater reserves, either via complete stop to withdrawals- a successful strategy in the case of industrial withdrawals in Venice, Italy (Margat and Van der Gut, 2013)- or via increased recharge. The use of artificial recharge systems, such as water banking in aquifers, can help (Maliva, 2014).

87. The main characteristics of potentially affected groundwater irrigation systems are related to the hydrogeological structure of the system and the degree of depletion of groundwater resources. Just like in the case of salinity, compactable aquifers, including those in sedimentary basins (sand and gravel), for which total withdrawal (from agriculture and potentially other sources) are significant relative to recharge may be among the most likely to be subject to land subsidence. The sensitivity of some of the most productive aquifers to these externalities, raises the question of whether their intensive use would be justified if such externalities were accounted for.

Groundwater recharge

88. One aspect that is not a challenge, but appears to be acting as a positive externality is the fact that agricultural land use, and in particular irrigated agriculture, can contribute significantly to recharge of water bodies including groundwater (Scott and Shah, 2004). The use of any type of water in fields, mostly used for evapotranspiration, can also result in partial seepage in the soil, leading to recharge of aquifers. In the first part of the 20th century, the mere conversion of land to rainfed agriculture in southeast Australia and southwest United States lead to significant increases in recharge and groundwater storage (Taylor et al., 2012). In central Spain, intensive groundwater pumping in the Upper Guardiana Basin has contributed to a net increase in water availability for consumptive use (Llamas and Garrido, 2007). Such mechanism is bound to be found especially in areas with shallow unconfined aquifers with rapid recharge.

89. Interestingly, irrigation-induced recharge is even more prevalent in such cases with inefficient irrigation systems. There is effectively a trade-off between the use of efficient irrigation systems, which allow saving water resources, and the level of recharge of aquifers they induce. Such effect will however only be observed at a significant scale in relevant aquifers where irrigation induced recharge is significant compared to natural recharge.

90. Yet, such recharge can also become problematic, when groundwater is not sufficiently used (Margat and van der Gun, 2013). In some conjunctive irrigation systems, in particular those with unconfined aquifers, surface water irrigation will increase recharge to the point of having the water table reaching a level close to the surface as suggested in Figure 11 (top panel). This can result in water logging, evaporation and salinity (Figure 14), and calls for proper drainage.

Conclusion

91. This report reviewed the status and characteristics of groundwater agricultural systems in OECD countries. The goal of the report was to set the scene on the importance of groundwater agricultural use, to determine whether and how agriculture groundwater systems can be compared by establishing common metrics, and to discuss what challenge it might entail.

92. First, using existing data from recent years, estimates of groundwater irrigated areas, uses and relative risks were reported for OECD countries. Groundwater irrigation is used on an estimated 23 million

hectares in OECD countries, which represents a third (33.5%) of the OECD total irrigated area. As of 2010, 60% of total groundwater withdrawal in OECD countries (or 229 km^3/year) was used for irrigation, which represents about a third of total groundwater irrigation globally. Incomplete data on trends at the country level showed that some of the top groundwater irrigating countries have increased their use in the past 25 years, while others may have maintained their use close to a long term average. The OECD average groundwater development stress for agriculture, which measures the ratio of use over recharge, was estimated at 7.6% in 2010, with large variations across members ranging from zero to over 100%.

93. Moving from country level to aquifer systems, some of the main differences in groundwater irrigation systems were introduced. Based on a review of existing typologies, a characterisation system was proposed for groundwater irrigation systems in OECD countries, to serve as a basis for management and policy responses. Agro-climatic conditions, relative access to and availability of surface water, access to and availability of usable groundwater resources and trends in groundwater use and profitability compared to competing demands from other sectors are identified as the four main factors to be considered. Each of these was then linked to primary and secondary variables, notably including geographic, geologic, and hydrogeological considerations.

94. Lastly, the main challenges and constraints of groundwater irrigation systems were presented. The use of groundwater irrigation can generate important external effects both on agriculture and the environment. In addition to pumping costs and directly related environmental externalities, the irreversible and drastic economic consequences associated with salinity and land subsidence were discussed. These challenges, and the lack of data in multiple settings, raise questions as to the economic incentives associated with intensive groundwater based farming. They also raise questions about the potential role of public policy around groundwater management. The two following parts of the report will look at these issues, analysing existing economic incentives and effects on one hand, and reviewing existing policies on the other, with a view to informing the policy debate and identifying possible solutions.

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ANNEX

Groundwater use in agriculture: complementary information, data and figures

95. This section presents a few additional figures on agricultural activities supported by groundwater. In the absence of maps drawing all activities, these are based on different countries and sources

Groundwater use for livestock and aquaculture

96. Water used for livestock is often ignored, given its proportion relative to field crop irrigation. However, it still can be significant in some countries.

97. In the United States, together with aquaculture it represents 4% of total groundwater use, but also standing for an industry worth USD 60 billion per year, much exceeding any field crop contribution (NGWA, 2013). Groundwater depending livestock is one of the pillar of the High Plains economy (Sophocleous, 2012b). An estimated 15 million cattle and 4.25 million hogs depend on the aquifer (Sophocleous, 2009).

98. In arid areas of Australia, groundwater provides the only source of drinking water for livestock, including in particular cattle and sheep, with a respective estimated value of AUD 393 million (Deloitte Access 2013).

Groundwater use for irrigated crops

99. Table 9 provides some data on the importance of groundwater in major field crops in the United States.

Table 9. Major crops using groundwater irrigation in the US

Crop	Number of farms using groundwater for irrigation	Irrigated area (ha)	Share of total groundwater irrigation area
Corn	28085	4.3 million	32%
Soybeans	21340	2.6 million	19%
Wheat	9535	1.1 million	8.2%
Cotton	5451	1.1 million	8.1%
Rice	3861	0.73 million	5.4%

Source: Derived from NGWA (2013). The last column is derived using total estimated area by Margat and van der Gun (2013).

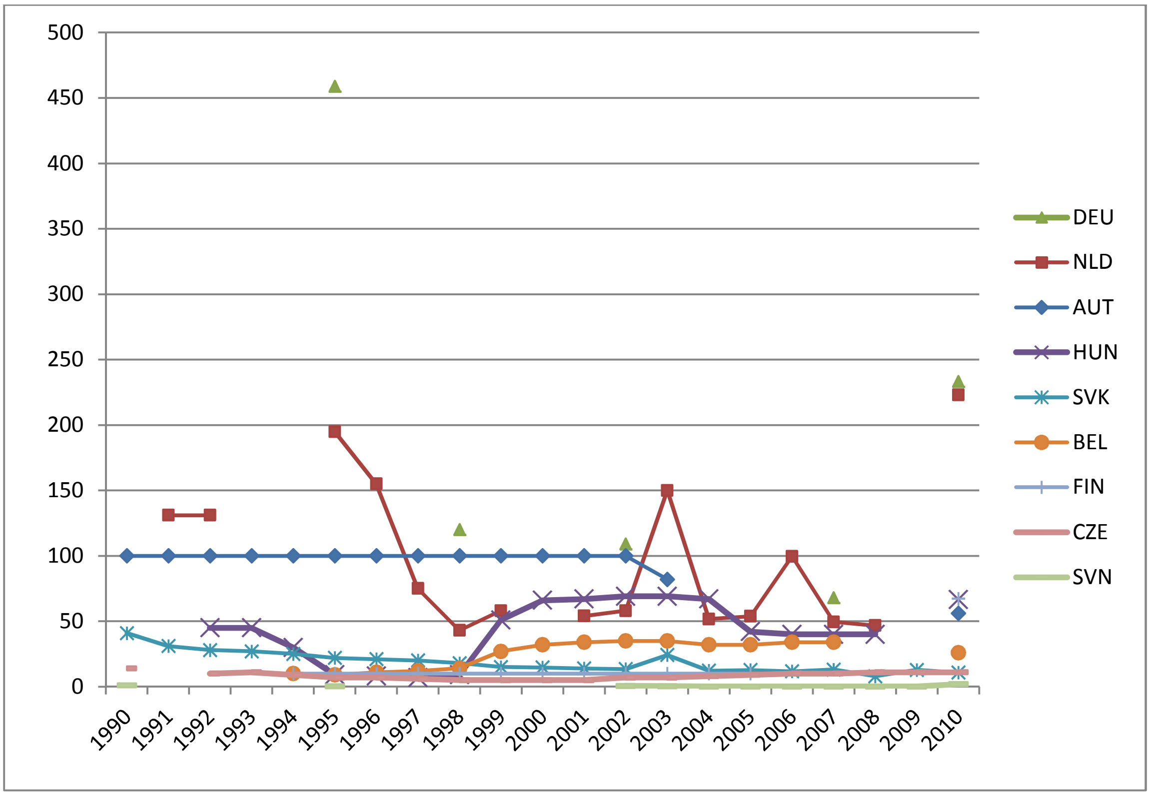
Additional figures and tables

Table 10. Groundwater areas and use in OECD countries

	Area irrigated by GW (ha)*	Share irrigated area*	Groundwater agricultural abstraction (km^3/year)**	Share of total groundwater abstraction**	Total groundwater abstraction (km^3/year)**
AUS	537030	21.1%	2.5792	52%	4.96
AUT	28481	83.2%	0.056	5%	1.12
BEL	1075	58.1%	0.026	4%	0.65
CAN	78551	8.6%	0.8041	43%	1.87
CHE	9900	22.0%	0	0%	0.79
CHL	58900	5.4%	0.7154	73%	0.98
CZE	1156	6.9%	0.011	3%	0.38
DEU	184796	78.8%	0.2332	4%	5.83
DNK	201480	100.0%	0.247	38%	0.65
ESP	1275563	37.1%	4.104	72%	5.7
EST	0	0.0%	0	0%	0.33
FIN	2250	15.0%	0.0672	24%	0.28
FRA	854248	44.6%	0.7994	14%	5.71
GBR	53039	39.8%	0.1944	9%	2.16
GRC	622765	48.1%	3.1025	85%	3.65
HUN	32782	22.0%	0.0666	18%	0.37
IRL	220	20.0%	0.0609	29%	0.21
ISL	0	0.0%	0	0%	0.16
ISR	88969	49.0%	0.8875	71%	1.25
ITA	893565	32.7%	6.968	67%	10.4
JPN	232143	8.9%	2.6256	24%	10.94
KOR	49639	5.6%	0.7327	17%	4.31
LUX	19	70.4%	0	0%	0.02
MEX	2191011	38.8%	21.204	72%	29.45
NLD	36089	58.0%	0.2231	23%	0.97
NOR	2505	5.8%	0	0%	0.41
NZL	156144	30.7%	0.48	60%	0.8
POL	7206	10.0%	0	0%	2.59
PRT	136183	54.9%	5.5981	89%	6.29
SVK	8193	7.8%	0.0108	3%	0.36
SVN	201	10.7%	0.0019	1%	0.19
SWE	18232	34.1%	0	0%	0.35
TUR	1729578	49.3%	7.932	60%	13.22
USA	13468649	60.2%	79.307	71%	111.7
OECD total	22960562		139.0376		229.05
OECD average		33.5%		30.3%	

Source:* IGRAC (2012), **: Margat and van der Gun (2013) and OECD (2013c) for the Czech Republic.

Figure 16. Agriculture groundwater use in other OECD countries from 1985 to 2010



Source: OECD (2013c) and Margat and van der Gut (2013) for the year 2010.

Existing typologies on groundwater and irrigation systems

Table 11. IGRAC groundwater regions in OECD countries and their characteristics

IGRAC region	OECD countries	Class	Main geology	Climate	Groundwater resources
1. Western Mountain belt of North and Central America	Western Canada, USA and Mexico	High relief folded mountains region	Basis of sedimentary and metamorphic rocks and volcanic rocks	From permafrost to oceanic and arid	Variable groundwater resources. Fluvial aquifer: (California Central Valley) Coastal aquifers. (Baja California)
2. Central plains of North and Central America	Central Canada, USA and Mexico	Sedimentary basin region	Thick layers of sedimentary rocks	Primarily dry	Rich resources, major aquifers: Ogallala, Northern Great Plains
3. Canadian Shield	Canada	Basement region	Crystalline rocks and a few sedimentary basins	Snow, permafrost	Limited resources
4. Appalachian highlands	Canada, USA	High relief folded mountains region	Metamorphic rocks with sedimentary basins	Humid	Variable resources mostly in carbonate rocks and sandstone aquifers, plus alluvial shallow aquifers
5. Caribbean islands and coastal plains of North and Central America	USA, Mexico	Sedimentary basin region	Alluvial and marine sedimentary plains, superimposed by volcanic rock (Caribbean)	Humid	Abundant resources in Alluvial sedimentary basins, largely karstic and some carbonate and volcanic aquifers
6. Andean Belt	Chile	High relief folded mountains region	Metamorphic, granitic, volcanic and sedimentary	Variable from humid to dry	Variable. Coastal sedimentary and volcanic aquifers.
10. Baltic and Celtic Shields	Estonia, Finland, Sweden, Norway, Iceland, Ireland, North West UK, and West France	Basement region	Mainly Crystalline rocks, Sedimentary (IRL), volcanic (ISL).	Medium to highly humid	Limited groundwater resources. Local karstic and volcanic aquifers.
11. Lowlands of Europe	Southeast UK, Southwest and Northeast France, Belgium, Luxemburg, Netherlands, Denmark, North Germany, Poland	Sedimentary basin region	Thick sedimentary plains	Medium humid	Abundant resources. Major aquifer (Paris Basin), limestone aquifer (Chalk aquifer in UK), sandstone aquifers.
12. Mountains of Central and Southern Europe	Portugal, Spain, Southwest France, South Germany, Switzerland, Austria, Italy, Czech Republic, Slovakia, Slovenia, Hungary, Greece.	High relief folded mountains region	Crystalline, volcanic and sedimentary structures	Dry to humid (Alps)	Variable resources, significant sedimentary basins (Po valley, Hungarian Plains)
23. North-western Pacific margin	Japan	Volcanic region	Sedimentary and volcanic rocks	Variable from dry to humid	Variable. Productive volcanic and sedimentary aquifers (Tokyo)

Table 11. IGRAC groundwater regions in OECD countries and their characteristics *(continued)*

IGRAC region	OECD countries	Class	Main geology	Climate	Groundwater resources
24. Mountain belt of Central and Eastern Asia	Korea	High relief folded mountains region	Crystalline, sedimentary rocks	Humid in coastal areas	Variable resources: karstified carbonate aquifers
26. Mountain belt of West Asia	Turkey	High relief folded mountains region	Crystalline, volcanic and sedimentary rocks	Dry	Variable. Significant resources in karstified limestone (Midyat aquifer in Turkey)
31. Levant and Arabian platform	Israel	Sedimentary basin region	Sedimentary valleys	Arid	Abundant but not renewable limestone complexes on the Mediterranean
34. Western Australia	Australia	Basement region	Crystalline rock, sandstone, karstified limestone and alluvial sediments	Arid to tropical humid (North)	Limited to moderate resources. Fissured sandstone (Canning aquifer) and limestone
35. Eastern Australia	Australia	Sedimentary basin region	Sedimentary alluvial formations	Arid to semi-arid more humid towards the coast	Moderate to high, major sandstone aquifer (Great Artesian Basin), Shallow alluvial sedimentary aquifers.
36. Islands of the Pacific	New Zealand	Volcanic region	Crystalline and sedimentary rocks (New Zealand)	Humid	Variable resources, some volcanic aquifer, and sedimentary (alluvial, marine) regions have significant resources.

Source: IGRAC (2004) and Margat and van der Gun (2013).

Table 12. Proposed typology of groundwater economies

	Arid agricultural systems	Industrial agricultural systems	Smallholder farming systems	Groundwater-supported extensive pastoralism
Countries	Algeria, Egypt, Iran, Iraq, Libya, Morocco, Tunisia, Turkey	Australia, Brazil, Cuba, Italy, Mexico, South Africa, Spain, United States	Afghanistan, Bangladesh, North China, India, Nepal, Pakistan	Botswana, Burkina Faso, Chad, Ethiopia, Ghana, Kenya, Malawi, Mali, Namibia, Niger, Nigeria, Senegal, South Africa, Tanzania, Zambia
Groundwater-irrigated areas	Less than 6 million hectares	6-70 million hectares	71-500 million hectares	More than 500 million hectares supported by boreholes for stock watering
Climate	Arid	Semiarid	Semiarid to humid, monsoon climate	Arid to semiarid areas
Aggregate national water resources	Very small	Good to very good	Good to moderate	Mixed rainfed livestock and cropping systems
Population pressure on agriculture	Low to medium	Low to very low	High to very high	Low population density but pressure on grazing areas is high
Share of total land area under cultivation	1-5%	10-50%	40-60%	5-8%
Share of irrigated area under irrigation	30-90%	2-15%	40-70%	<5%
Share of irrigated area under groundwater irrigation	40-90%	5-20%	10-60%	<1%
Share of total geographic area under groundwater	0.12-4.0%	0.001-1.5%	1.6-25.0%	<0.001% but groundwater supported grazing areas about 17% of total
Organization of agriculture	Small to medium size farms under market based agriculture	Medium size to large scale farms under industrial, export-oriented farming	Very small landholdings, subsistence-oriented, mixed peasant farming systems	Small-scale pastoralists, often seasonally connected with small-scale agriculturalists
Driver of groundwater irrigation	Lack of alternative irrigation or livelihood	Highly profitable market-based farming	Need to absorb surplus labour in farming through land-augmenting technologies	Stock watering
Significance of groundwater irrigation to national economy	Low (<2-3% GDP)	Low (<0.5% GDP)	Moderate (5-20% GDP)	Moderate (5-20% GDP)
Significance of groundwater irrigation economy to welfare of national population	Low to moderate	Low to very low	Very high (40-50% of rural population and 40-80% of food production involve groundwater irrigation)	Low in terms of numbers of pastoralists involved, sometimes moderate in terms of national food supply
Significance of groundwater irrigation for poverty reduction	Moderate	Very low	Very high	Groundwater central to pastoral livelihood systems, but limited scope for using more groundwater for poverty reduction
Gross value of output supported by groundwater irrigation	USD 6-8 billion	USD 100-120 billion	USD 100-110 billion	USD 2-3 billion

Source: Shah et al. (2007).

Table 13. The GW-MATE typology of groundwater systems

Overall typology of groundwater body	Sub-divisions by type of situation or process involved
(1) At risk of extensive quasi-irreversible aquifer degradation and subject to potential conflict amongst users	(a) Under intensive exploitation (b) Vulnerable to widespread pollution from land surface (c) Undergoing depletion of non-renewable storage reserves
(2) Subject to potential conflict amongst users but not at risk of quasi-irreversible aquifer degradation	(a) With growing large-scale abstraction (b) Vulnerable to point-source pollution (c) With shared international/interstate resources
(3) Insufficient (or inadequate use of) scientific knowledge to guide development policy and process	(a) But potential to improve rural welfare and livelihoods (b) With presence of natural quality problems (c) But scope for large-scale planned conjunctive use

Source: Foster et al. (2009).

Table 14. Proposed typology of groundwater and surface water resources use in irrigation depending on climatic conditions

	Favourable conditions for groundwater withdrawals (high transmissivity and storage volume)	**Unfavourable conditions for groundwater withdrawals** (low transmissivity and storage volume)
Unfavourable climatic conditions (low groundwater recharge)	Irrigation using recharge from surface water and groundwater (if surface water generated in areas with favourable climate is available) or irrigation using non-renewable groundwater from deep wells	Surface water irrigation (from canals, rivers or reservoirs) using runoff generated in areas with favourable climatic conditions
Favourable climatic conditions (high groundwater recharge)	Irrigation using mainly renewable groundwater from springs and wells	Surface water irrigation (from canals, rivers or reservoirs)

Source: Siebert et al. (2010).