Chapter 2

Defining and identifying water risks for agriculture

This chapter defines the key characteristics of a hotspot approach to agriculture water risks. It then applies this approach at a global level, using data from the literature, to identify future water risk hotspot countries for agriculture production. The evidence points to the People's Republic of China, India and the United States as the leading agricultural producing countries most likely to be impacted. Specific water risks within these countries, in the identified key agriculture production regions of Northeast China, Northwest India and Southwest United States, are reviewed.

Key messages

The “hotspot” approach focuses attention and action on locations where the risk is highest relative to other locations due to higher hazards, exposure or vulnerability within a broader approach to risk management. This approach presents clear advantages for policy makers. It lowers the cost for an achievable result, helps prevent the diffusion of risks, and focuses attention and efforts on specific regions. It can be applied at virtually any scale for individual or multiple risks, and can account for all dimensions of water risks in a limited number of spots.

This approach is particularly well suited to agriculture water risks given the local specificities and dynamics associated with agriculture and water that make it difficult to propose generic approaches to risks. The hotspot approach can also help control pollution and support customised adaptation to climate change.

Application of the hotspot approach is only effective under certain circumstances. There are three main conditions that must be met: (1) risks should be non-uniform at the national level; (2) high-risk regions should be well-defined and bounded; and (3) hotspot assessments should be supported by robust information and data.

Employing the hotspot approach to agriculture water risks involves two steps: defining agriculture water risks and determining a threshold to identify what constitutes a hotspot. Both steps will vary depending on the scope, scale and time horizon, as well as the level of information.

The hotspot approach was applied to future agriculture production at the global level – using a combination of a literature review on water risks and existing agriculture projection – to determine countries at high risk. This exercise identified China, India, and the United States as the top three water risk hotspot countries for agriculture production. While many other countries and regions are expected to face high water risks that will affect their agriculture production, these three countries are distinguished by the fact that they concentrate high levels of water risks and projected high shares of global agriculture production.

Three key agriculture production regions within these countries are expected to face particularly high water risks: Northeast China, Northwest India, and the Southwest United States. These regions face similar water issues such as low and variable surface water supplies, groundwater depletion, and expected increased demand from other sectors. Water quality issues are also prevalent in Northeast China and could arise in Northwest India.

2.1. Rationale and conditions for a robust hotspot approach

The "hotspot" approach focuses attention and action on locations where the risk is highest relative to others due to higher hazards, exposure or vulnerability, within a broader approach to risk management.[1] The management of risks can operate at different levels. Public policy can be set at the international, national or sub-national levels when considering broad types of risk, and prioritisation may help advance a strategy or investment among multiple risk dimensions. In practice, all broad applications, prioritisations, or hotspot approaches may act as a complement for different types of risks in response to general or critical risks. This approach does not aim to replace overall management of water resources and the necessary broader approach to risks, but aims to act as a complementary policy for higher effectiveness when faced with critical risks.[2]

The hotspot approach has multiple advantages when risks are geographically concentrated. First, it allows for gains in efficiency by lowering the cost of an achievable result. Financing measures that prioritise actions to address the most critical risk areas deters investment in lower priority risks that have limited beneficial outcomes. Second, it may prevent the diffusion of risks; advanced targeting is often a key component of pollution or sanitary damage control to prevent wider impact. Third, when applied *ex ante* to vulnerable areas, it can help focus attention and efforts on uncertain futures (FAO, 2015a). Fourth, since it is an approach based on relative levels of risks, it can be applied at virtually any scale for multiple risks. Lastly, the focus on hotspots enables an all-encompassing response to risks, taking account of all dimensions of water risks in a limited number of hotspots, from water scarcity to water quality and variability. This approach may serve as a learning process to gradually address a greater number of areas with lower risks.

In the context of this study, the hotspot approach identifies specific locations that are most likely to be subject to agriculture water risks in the future, because they are, or will be, significant agriculture producing regions and are they expected to be under water constraints. For the purposes of this report, water risks are defined as the combination of different types of water constraints: insufficient water, water abundance, water quality impairment, and water-related catastrophic events (see Annex 2.A1). The objective is to identify and put in place effective responses that are specifically adapted to locally important risks for agriculture. While some of the responses may include options that are not locally specific, such as varietal breeding or efficient irrigation systems, the intensity and combination of responses need to match the scale of the local challenges (Chapter 4).[3] For instance, agriculture regions with groundwater intensive use that leads to multiple environmental externalities, as observed in California, require a combination of advanced responses, from increased information to collective action, and the use of regulatory and economic instruments, that are not needed in areas not facing the same problems (OECD, 2015a).

In this context, the hotspot approach may have several additional benefits:

- A narrow scope can help target water risk mitigation policies in areas where impacts will most likely be critical. As agriculture activities vary geographically, the sector's vulnerability to and impact on water risks will also differ locally. This is particularly the case for large countries or regions with a diversity of climatic conditions and agriculture systems.
- This approach can mitigate water quality risks, whether associated with point source or diffuse pollution, spread via surface waterways and groundwater bodies. Targeting is a key recommendation for effective water quality management (OECD, 2013), including in agriculture (OECD, 2012).[4]
- The hotspot approach can also be a means to design high return, locally-customised climate adaptation plans that account for productivity objectives. The efficiency and effectiveness of public intervention can be enhanced by knowing more about where and how to act (Ignaciuk, 2015).
- It allows for policy actions that consider the cumulative effects of multiple hotspots risks materialising simultaneously. Projections can present climate-related water impacts affecting demand and supply in different regions simultaneously. For example, the Russian heat wave and the Pakistan flood that occurred simultaneously in 2010 were climate-related (Lau and Kim, 2012), and likely had consequences on global food markets.

- The proposed approach can be employed at different agriculture, geographical or administrative levels as needed. Targeting for policy purposes will generally be more relevant at the national level, but state or province level may also be more appropriate in countries with federal government systems. Watersheds can be set as unit subject to prioritisation, or targeting can also be done within a specific watershed.

It should be noted that applying future water risk hotspots for agriculture does not necessarily imply that current allocation of efforts is not effectively suited to respond to water risks. Instead it encourages further policy efforts in this direction, especially considering future water risks that may not be currently addressed, either because they do not cover the same area, or because the risks are likely to further increase in areas facing current risks. Baseline projections of water risks show that the cost of no additional action can be significant (e.g. Chapter 1), the hotspot approach essentially aims to focus on areas where this cost is expected to be the greatest.

Conditions for the beneficial application of the hotspot approach

The relevance of the hotspot approach relies on the presence of a non-uniform distribution of risks in space, time, or hazard intensity (see Annex 2.A1 for definitions). For example, a large aquifer could be at risk of complete depletion, but the timeframe for depletion is unknown, if it occurs, the impact could vary depending on type of user and location, including users across country borders. Overall, the water cycle is subject to major non-uniformities, from variations in climate and precipitation to interactions with continental landscapes, ocean currents, local temperature, and human activities; "Availability of water is very different across geographical regions, both in terms of rainwater, and of surface and ground water. Therefore, water availability needs to be considered at regional, national and local levels" (HLPE, 2015).

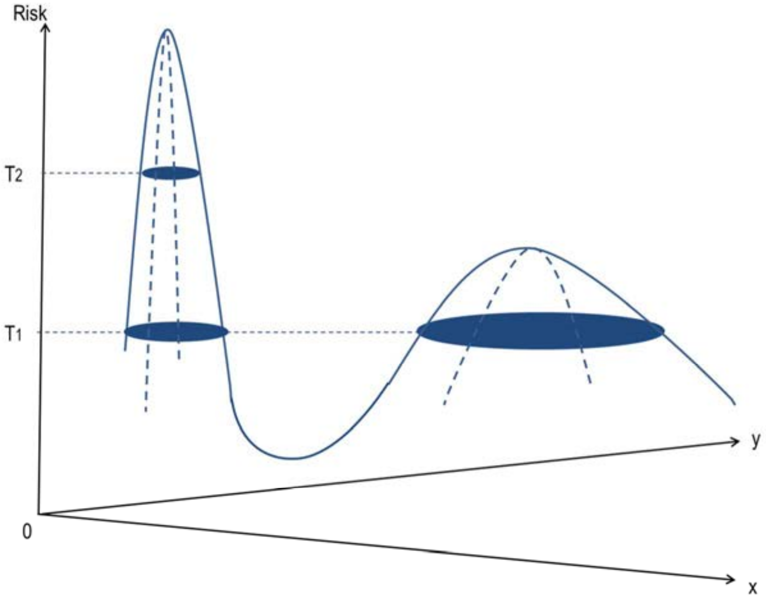
The usefulness of this approach is also determined by the presence of well-defined risk peaks, or regions of relatively high risks, that are sufficiently narrow but still significant in scope (Figure 2.1). A wide distribution of low risks reduces the effectiveness of the hotspot approach. For example, if salinity affects a whole continent with a relatively low overall impact, a hotspot approach may not be as useful as compared to a limited portion of a highly productive agriculture coastal area at risk from salinity. At the same time, punctual discrepancy in risk profiles (outliers) should not qualify as peaks, and a sufficiently large area or activities needs to be affected for the corresponding area to be considered a hotspot. These conditions will depend on the water problem and results of the risk assessment process.

Effectively targeting risk requires sufficient knowledge and information. Hotspot assessments must be sufficiently robust to avoid potentially costly mistakes, particularly when considering future risk hotspots. Missing a hotspot—a statistical type II error—could be costly. A high cost could also be associated with investing in institutional efforts, funding or regulatory actions on a site or region that turns out not to be at risk (a statistical type I error). Avoiding such mistakes requires gathering sufficient water risk data and providing trust-worthy estimations of risks using multiple hypotheses, scenarios and sources for validation when and if possible.

Finally, the hotspot assessment must be undertaken at the appropriate scale. Too large a scope may neglect important local problems. Similarly too narrow a scope may result in excessive attention to specific problems to the detriment of important issues observable at a broader scale. There may be trade-offs to consider in national versus regional hotspot assessment.

Setting the proper threshold to distinguish hotspot areas from non-hotspot areas requires accounting for these conditions. There is an inherent trade-off between the selected threshold level, which increases efficiency and impact, and the coverage of the assessment (as illustrated in Figure 2.1). Under conditions of perfect knowledge, such a trade-off could be resolved via a cost-benefit analysis, but under conditions of uncertainty on hotspots, decision makers must decide the extent to which savings must be sacrificed to avoid possible mistakes.

Figure 2.1. Selecting a threshold for risk hotspots requires balancing focus and coverage



Note: The curve shows the evolution of risks, defined as exposure multiplied by expected hazard, in the (x,y) space. Cutting at level T_1 allows including two hotspot areas of potential importance, but could create significant costs and lower efficiency, cutting at T_2 increases focus, reducing actions to one hotspot with more likely effective response but potentially insufficient scope.

Source: Author's own work.

2.2. Assessing water risk hotspots for agriculture production: Methodology and application at the global level

Main steps to identify water risk hotspots for agriculture

There are two steps to identifying agriculture hotspots (Annex 2.A1).

- *Definition.* Defining future water risk hotspots for agriculture requires the measurement of water risks affecting agriculture and plausible ways to project these risks in the future. There are multiple indices used to measure water risks, each with its own advantages and possible limitations. Choosing the right index will depend on the type of risks and availability of data and/or modelling means (Annex 2.A1). Identifying hotspots also requires credible agriculture projections. Both water risk and agriculture projections will depend on the specific time horizon and geographic scope. The two types of projections need to be combined or integrated: agriculture conditions (in the absence of risks and responses) and water risk assessments.

- *Setting appropriate thresholds to define hotspots.* There are several options to consider depending on the degree of detail taken in the first step of the assessment,. Where the future water risks and agriculture projections are well known, thresholds can be determined on the basis of the distribution of risks on agriculture (or the estimation thereof). Under partial or incomplete information on future water risks hotspots for agriculture, the objective is to look for regions with a consistently higher level of projected agriculture water risks (combined water risks and agriculture importance) relative to other regions based on available evidence. Where critical information on water risks or agriculture is unavailable, or where information focuses on a limited area, a hotspot approach may not be recommended.

Annex 2.A1 provides a more complete explanation on the methodology used to define water risks, identify agriculture water risk hotspots, including regional and national examples of applications of water risk hotspot approaches from the European Union and the United States, Australia, Switzerland and New Zealand. The next section explains the method used to identify the globally-significant agriculture-producing countries subject to future high water risks.

Application: Searching for globally significant water risk hotspots for agriculture production

The objective of the present application is to identify countries where agriculture production is projected to face the highest water risks and have significant global impact. In this application, agriculture production levels certainly matter but only as far as such production will face high water risks. This implies that countries with high water risks and low projected production or countries with high agriculture production and water risks may not be identified as hotspot compared to others. In contrast, countries that concentrate production and water risks criteria have a global significance in that there response to water risk may affect global markets and therefore a wider range of countries. The water risks considered include shortage, excess, and water-quality related, as defined in Annex 2.A1.

Applying a hotspot approach to water risks at the global level is a difficult exercise. It requires extensive inquiries as well as a process to address multiple uncertainties. The models used need to pull from sufficiently well-calibrated data in all regions of importance. There may be significant uncertainties associated with assumptions for both water and agriculture. On the water risk side, climate change effects and demand expectations from agriculture and other sectors may be uncertain (Buckle and Mactavish, 2014; OECD, 2014a, see Box 2.1). For the agriculture sector, the critical issue is to assess the future of the sectors in the absence of risks —i.e. establishing a credible counterfactual— to ensure that risks within the hotspots are indeed important.

Box 2.1. Projecting water risks associated with climate change: A confluence of uncertainties

There is clear value in trying to project climatic conditions and to use them in hydrologic assessments. They provide insights on broad trends that can be useful if not critical to water managers operating in areas under growing water stress. But these projections also face a number of challenges and uncertainties.

Multiple researchers note that, contrary to temperature, simulating changes in water cycles is challenging. Like any climate projection, they first face multiple uncertainties stemming from: (1) scenarios of future greenhouse gas emissions by integrated assessment models; (2) translation of greenhouse gas emissions scenarios into atmospheric concentrations and forcings; (3) evaluation of the effects of these forcings on climate by global climate models (GCMs); (4) downscaling and bias-correcting the output of the GCMs; and (5) translation of climate change projections into impact projections by impact models, e.g. hydrological or vegetation models (Döll et al. 2015). National rainfall projection uncertainties, in particular, require periodical bias corrections between simulated and historical data to be of use. Inherent uncertainty in computing freshwater-related hazards adds to this picture, as there is generally scarce information on the state of freshwater systems (Ibid.).

These uncertainties render the results of quantified simulations potentially unrealistic. Döll et al. (2015) argue that these exercises provide probabilities of possible future water risks and hazards. There is some evidence to suggest that even with broadly based results, the recommendations they provide may have little value. A review of the application of 28 World Bank studies using climate projection models found that they are often used as a backdrop for urging the adoption of "no-regret" actions, and rarely for quantitative decision making on options". The review concludes that climate model information has generally been unable to inform quantitative decision making in the surveyed sample […] over half of the studies recommended low-regret adaptation options that do not depend on climate projections, and roughly one-quarter did not recommend adaptation options" (IEG, 2011).

The use of models for broad hotspot mapping is also questioned by researchers. De Sherbinin (2014) argues that in many cases data-driven maps show patterns that would have been identified in an expert assessment approach or based on a broad understanding of past patterns. In particular, regions that have the lowest levels of economic development are typically found to be most at risk in global hotspots mapping assessments" (Ibid.).

Source: Döll et al. (2015); de Sherbinin (2014); IEG (2011).

There are also important caveats to this particular application of the hotspot approach, which focuses on water risk for agriculture production at the global level.

- It relies entirely on secondary data and available literature and therefore represents an example of hotspot determination based on an incomplete assessment. The hotspot application is based on a finite sample of studies on global water risk that does not aim to be fully comprehensive. The dataset derived from the literature uses multiple types of models that are not always comparable.[5] While combining results from multiple approaches helps provide some robustness that single simulation studies may lack, the results of the proposed assessment must be viewed as a second-best assessment of future water risks in agriculture.
- It provides a snapshot of evidence that can evolve over time. New areas and countries may become hotspots tomorrow with unpredictable changes in climate or water use.
- The present exercise is done at a global level with countries as the primary unit of analysis because of data and analysis limitations (superposing precise geographic data would require compiling all data from the large range of studies, which are not available). This means that the size of countries matters in the exercise given the relationship and impact this factor has on agriculture production levels. At the same time water risk level do not follow country borders and may be highly concentrated in areas with small or larger countries.[6]
- The emphasis of the assessment is to look at future water risks; therefore, most studies assess water risks relative to the current risk status of countries. As a consequence countries with high water risks today but projected favourable future climatic conditions may not be singled out as subject to high risk in the assessment.
- The proposed application, which focuses on agriculture production, is more likely to consider regions with significant importance for global food security than regions that have greater local and regional food security issues. Multiple regions and countries where local agriculture is critical for the local populations, face high water risks, and yet may not be identified as hotspots. The methodology put forth in this assessment accounts for the fact that agriculture products are increasingly traded and international trade could therefore act as a tempering mechanism for agriculture water risks of local importance. In contrast, in the case of high risks for globally important agriculture countries, water constraints could lead to global supply imbalances and much larger market effects with possible food security implications. Integrated modelling that accounts for water, climate, and food security risks could help even if the hypotheses and scenarios may limit the robustness of the results.
- Vulnerability is not as a core criterion for hotspot selection given the lack of consistent data on future vulnerability to water risks for agriculture and the emphasis on risks that will have an impact on global food production, Instead, the methodology prioritises the likelihood and expected agriculture production impacts.

The assessment relies on the geographical decomposition of results from 64 global-level studies with water risks measurements (see Annex 2.A2 for details). These studies assess the different types of water risks associated with climate change and/or demand projections, focus on surface water and/or groundwater in the current, medium term or long term, all at the global scale. Most studies focus on water risks for all sectors and not specifically agriculture, and a few studies look at vulnerability. Most focus on likelihood and intensity of impacts (measured in different ways, see Annex 2.A1). To the extent possible, the assessments use business as usual or no action scenarios as opposed to scenarios with simulated responses (e.g. water risk adaptation or mitigation of risk).

The hotspot approach uses the frequency in observations considering that a region is of high risk as a primary metric for eligibility. Countries are considered—and accounted for in the computation of this frequency— if they are categorised in the high or highest risk categories or if they are identified in any report as facing the most severe water risks. Availability of data across countries is a limiting factor of this indicator, which could lead to inconsistency in results with respect to level of risk by country. However, given the global focus of the hotspot approach, the overwhelming majority of reviewed studies uses genuine global simulation models that span through all continents, preventing a systemic bias. Furthermore, the consistency across studies that frequency measures may reflect research preference for types of modelling (model, scenarios etc.), but does not guarantee that such methods are the best. At the same time, it reduces the possible bias associated with using one single model.

On the agriculture production side, the methodology considers a set of widely used commodities in the medium run and the longer run, presuming absence of water or climate risks (counterfactual scenario). These countries are or will become agriculture hotspots because their production sustains a significant share of the world's aggregate supply. This is done by collecting estimates of production and exports for coarse grains, rice, wheat, oilseeds, sugar, cotton, dairy, and beef from the OECD-FAO Agricultural Outlook 2015 (OECD/FAO, 2015) for 2024, and the same commodity from the baseline scenario of IFPRI's IMPACT model for 2050 (Robinson et al., 2015). The fruit sector was also looked at for 2050 as it may be affected by water (but is not specifically separated in the AgLink-Cosimo model). The indicators for agriculture weights are defined as the average shares of production for the selected commodities and time horizons.

Future water risk hotspots are then selected by cross-referencing information on water risk with information on agriculture production (presence of a water risk as indicated with the frequency of high risk index and high share of production). No explicit threshold is assumed a priori, as the determination is completed by relative comparison. Those countries or regions with consistently higher risks and higher agriculture market shares in at least some of the key commodities are potential candidates for future water risk hotspots for agriculture.

2.3. China, India, and the United States concentrate global agriculture production water risks

The determination of water risks was based on 118 observations of water risks (current or future), from 100 individual analyses, coming from 64 publications of global water risks (including risks in agriculture), which are listed in Annex 2.A2. Table 2.1 shows the distribution of observations; the overwhelming majority focuses on water scarcity risks.

Table 2.1. Distributions of observations from the literature review

	Risk of shortages	Risk of excessive water[1]	Risk of climate variability[2]	Water quality risks	Total
Future	59	20	4	3	86
Current	28	3	1	0	32
Total	87	23	5	3	118

1. Includes risks of flooding generated by sea level rises.

2. This category regroups observations that capture the probability of extreme events lump together. Observations for extreme floods or droughts were counted under shortage and excess, respectively.

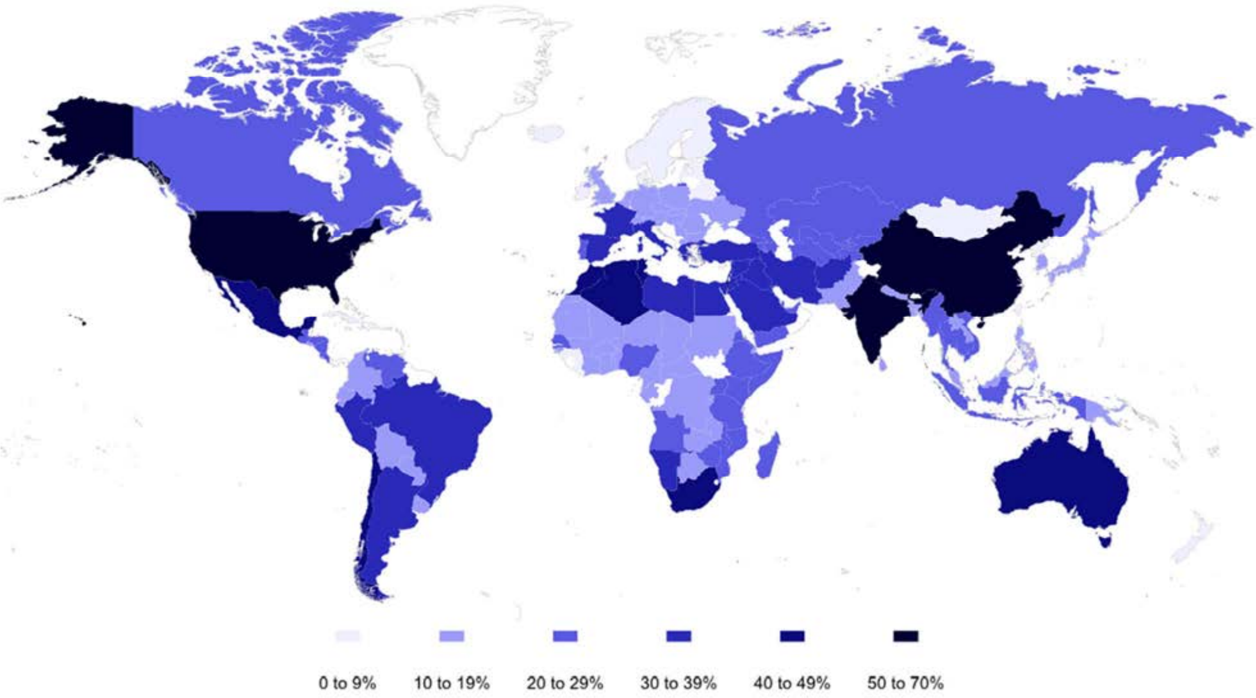
Source: Author's assessment based on the reviewed literature.

The location of hotspots was most often determined directly from maps of risks, using tables provided by the publications studied, and/or by looking at the authors' assessments and analysis of the most severe risks. These results were reported by indicator variables – a value of 1 assigned if the risk is prevalent, and a value of 0 assigned for non-prevalent risk – for 142 countries.[7] Results reported in publications at the regional level (e.g. Middle East or North Africa) were then accounted for at the country level for the corresponding countries in the region (e.g. Algeria was allocated a 1 if North Africa was considered a hotspot in a study).

The most severe water risks were found in two bands of countries largely in the north and south subtropical zones (Figure 2.2).[8] For countries that are subject to high risks in at least 30% of observations, results were decomposed into four categories of risks: shortages, excess, variation (probability of extreme events), and quality (Figure 2.3). Thirty countries are in this set. The leading three countries – China, the United States and India – were found to be at high risk in over 55% of the measurements.[9] Fifteen countries follow, with the proportion of high risks observations between 40% and 50%, mostly from the Mediterranean region. The remaining 16 countries are relatively spread out and diverse. Ten OECD countries feature in this list: Australia, Chile, France, Greece, Israel, Italy, Mexico, Spain, Turkey, and the United States.

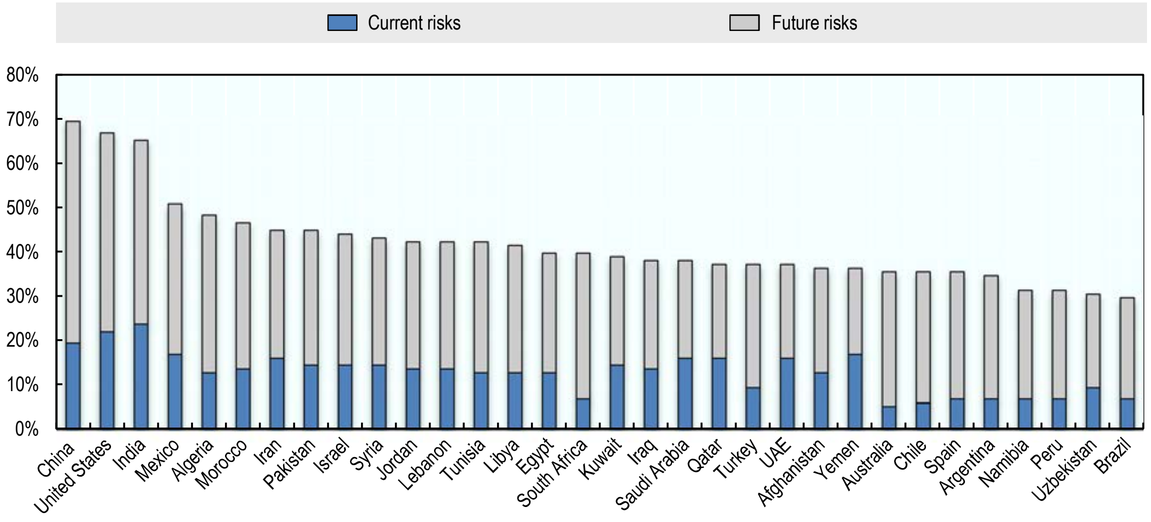
Figure 2.2. China, India and the United States are expected to face the most water risks

Frequency of observations, listing countries as subject to high or very high future water risks



Source: Review of 64 publications, accounting for 142 countries.

Figure 2.3. Proportion of severe water risk observations for the leading countries in the reviewed literature



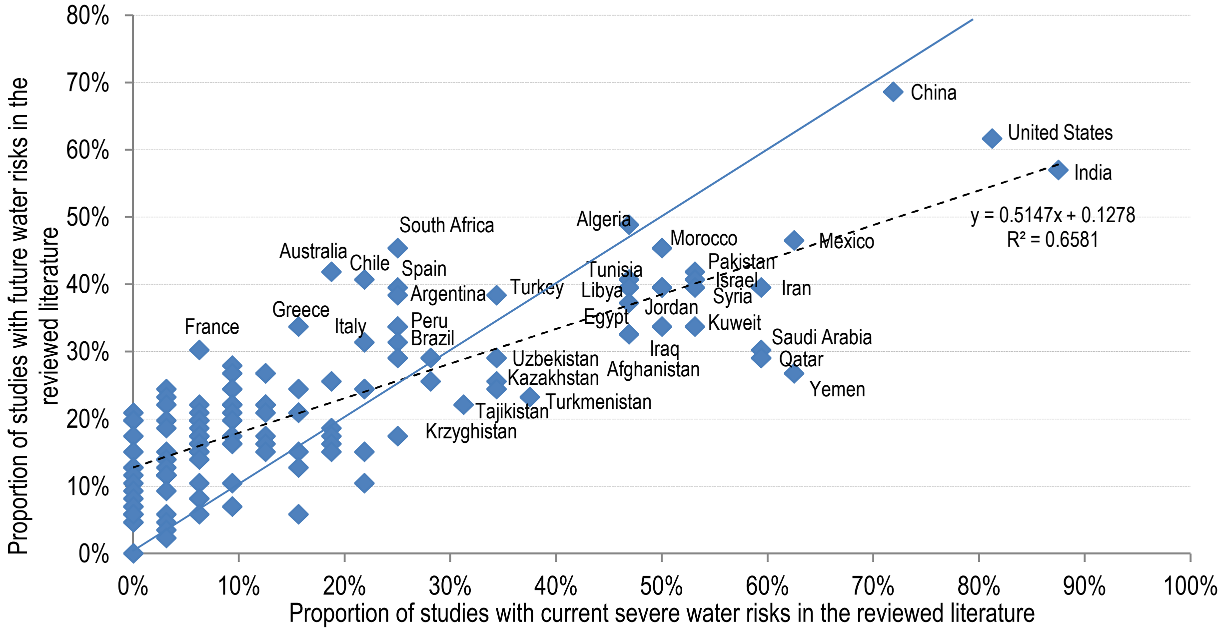
Source: Derived from an analysis of 64 studies.

Comparing observations of current and future risks (Figure 2.4) helps distinguish four groups of countries: the three leading countries (China, India and the United States) featuring the highest current and future risks; a second group of countries (located mostly in North Africa and the Middle East) with high current and future risks; a third group of countries with moderate to high risks (that includes Mediterranean, Latin American and Southern African countries); and a large group of countries subject to comparatively lower future water risks (< 30% in both dimensions).

Most countries that have high indicators for current water risks have relatively lower indicators for future water risks (they are located under the median), and conversely most countries with lower indicators for current water risks have higher indicators for future water risks (above the median).[10]

Looking at the type of risks (Figure 2.5), if most countries are subject to risks of shortages, the leading three countries (China, the United States and India) are subject to the three main risks (shortage, excess and quality). More broadly, Table 2.2 shows that China, India and the United States feature among the top listed countries in multiple categories of risks.

Figure 2.4. Countries with lower current water risks may face relatively higher risk

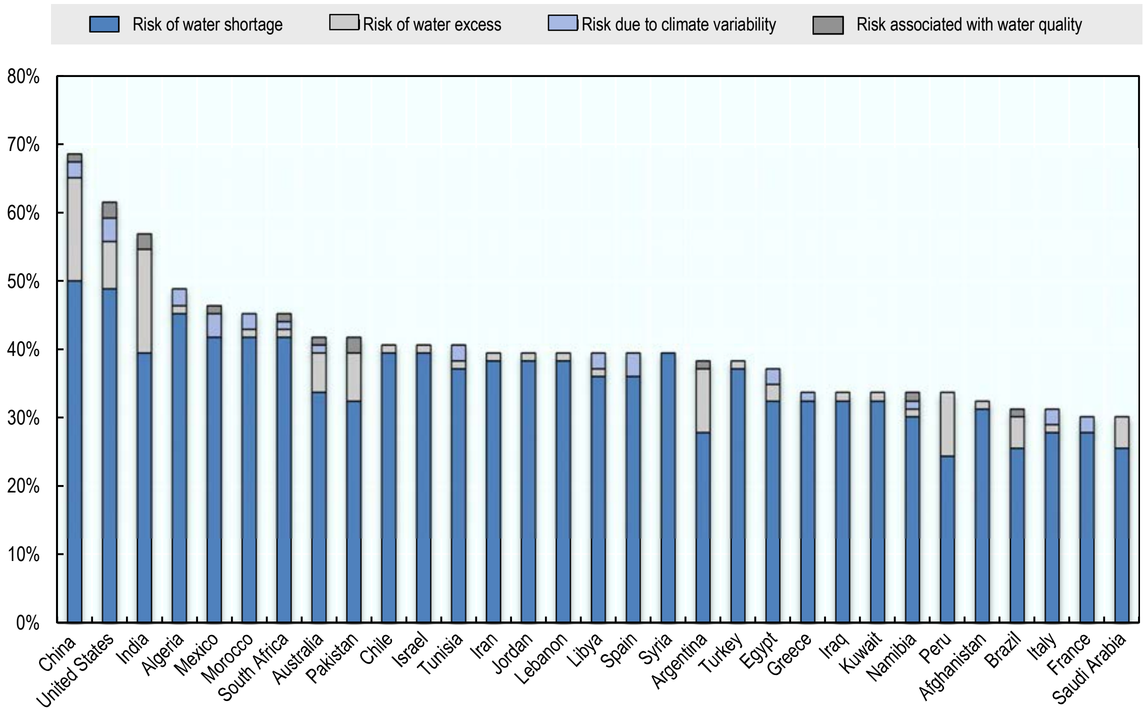


Note: Shares of severe water risk future and past observations, across reviewed studies.
The continuous line represents the median (y=x), the dashed line is a linear regression.

Source: Derived from the analysis of 64 studies.

Figure 2.5. Proportion of severe future water risks, by category, reported in the reviewed literature

Only countries with overall proportion above 30% are listed



Source: Derived from the analysis of 64 studies.

Table 2.2. China, India and the United States lead the rankings for different types of water risks

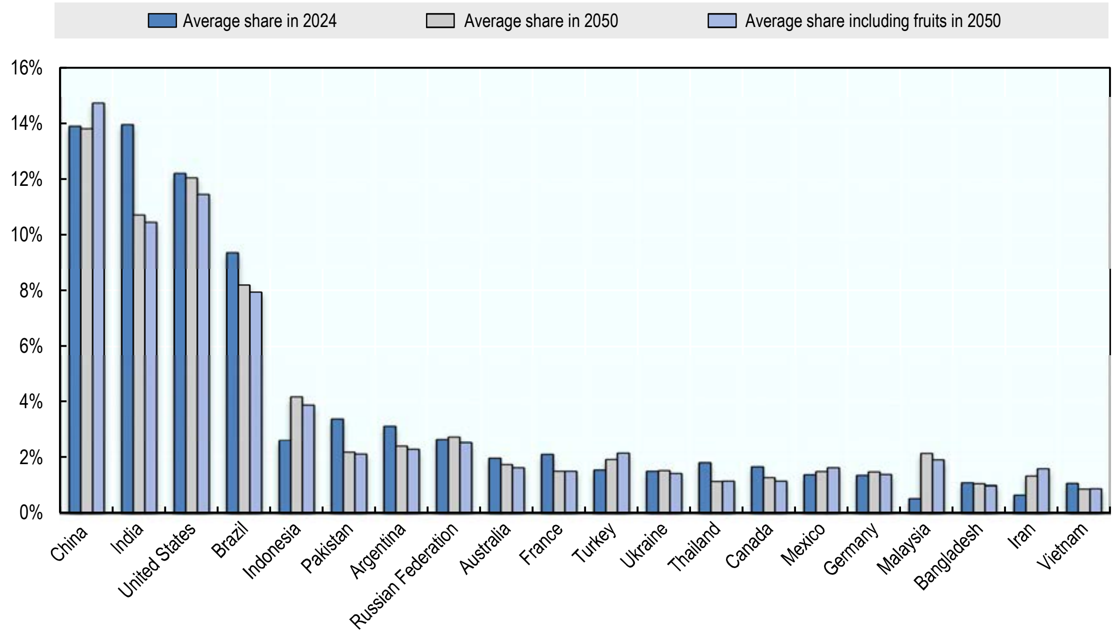
Future water risks aggregate index	Future risks of water shortages	Future risks of excess water	Future risks of variability	Future risks of water quality
1. China (69%)	1. China (73%)	1. China, India (65%)	1. 12 countries including the United States (75%)	1. India, Pakistan, United States (67%)
2. United States (62%)	2. United States (71%)	3. Cambodia, Indonesia, Myanmar, Viet Nam (55%)		
3. India (57%)	3. Algeria (66%)			

Source: Review of 64 studies.

Looking ahead at the agriculture production for 2024 and 2050, Brazil, China, India and the United States account for about 50% of the average global production (Figure 2.6). These large countries consistently lead production rankings across almost all categories of products, whether currently or in 2024 and 2050 baseline projections. The four countries that follow — Argentina, Indonesia, Pakistan, and the Russian Federation — are projected to have significant production shares in at least a few markets for one or the other model. The twelve remaining countries appear either to have strong specialisations (e.g. Thailand for rice) or a non-negligible contribution in several markets (Ukraine).

Results from the two model projections (AgLink-Cosimo and IMPACT) are reconciled by taking average shares to represent medium-term projections (2024 from AgLink-Cosimo and 2050 from IMPACT) across commodities, keeping the average shares from IMPACT for 2050 with or without fruits to capture the longer term. Differences across models can be explained by the models' differences in structure, projections and hypotheses. Furthermore, some countries are only covered in one of the databases.

Figure 2.6. Average production shares of major agriculture commodities for the 20 largest producers, 2024 and 2050



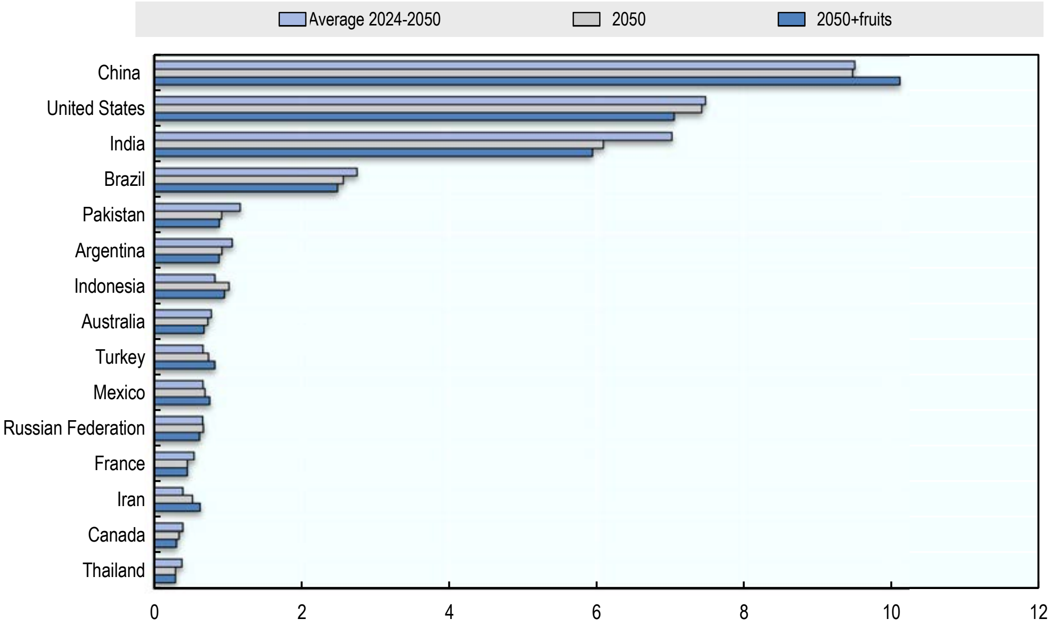
Note: Eight commodities are included: coarse grains, rice, wheat, sugar, cotton, oilseeds, dairy, and beef.
Source: Derived from baseline projections from the AgLink-Cosimo model for 2024, and from the IMPACT model for 2050.

The index representing future water risks for agriculture is computed by multiplying the proposed agriculture and water risk indicators, i.e. the proportion of measures reporting water risk in the future by the average shares of agriculture production (average of 2024 and 2050 as core, 2050 with the same commodities, and 2050 with fruits as addition), and a factor of 100. As such, the index can be interpreted as the expected share of overall global production of the selected commodities likely to face high water risks in each country in the medium to long run under no adaptation action. This index is computed for 77 countries that are the most significant agriculture producers of each commodity, representing altogether over 86% of total projected 2050 production of each commodity. It also includes countries of the OECD, ASEAN, and the Mediterranean region. The results are shown in Figure 2.7 for the top 15 countries, in Figure 2.8 comparing the leading countries to the aggregate index for selected regions, and in Figure 2.9 globally (OECD results are shown in Annex 2.A2, Figure 2.A2.1).

Figure 2.7 shows that three countries stand out from the analysis: the United States, China and India. These countries are expected to remain the leading international agriculture producers but also rank highest in terms of projected water risks. Their land and population scope may contribute to this ranking, although this is not sufficient to explain the high agreement across studies on the presence of future water risks (55% to 70% of observations report severe water risks of different kinds). To ensure that the size effects does not dominate the diagnostic, regional rankings for three multi-country regions with large shares of agriculture production and significant water risks were computed for comparison; the 14 Mediterranean coastal countries (which includes countries from North Africa, Southern Europe and the Near-East), ASEAN (Southeast Asia) and 21 European Union countries members of the OECD.[11] As shown in Figure 2.8, none of these regional groups exceeds half of the index of each of the three top countries. On this basis, and acknowledging the previously listed limitations of this global country-level analysis, China India and the United States are identified as future water risk hotspots for agriculture production.

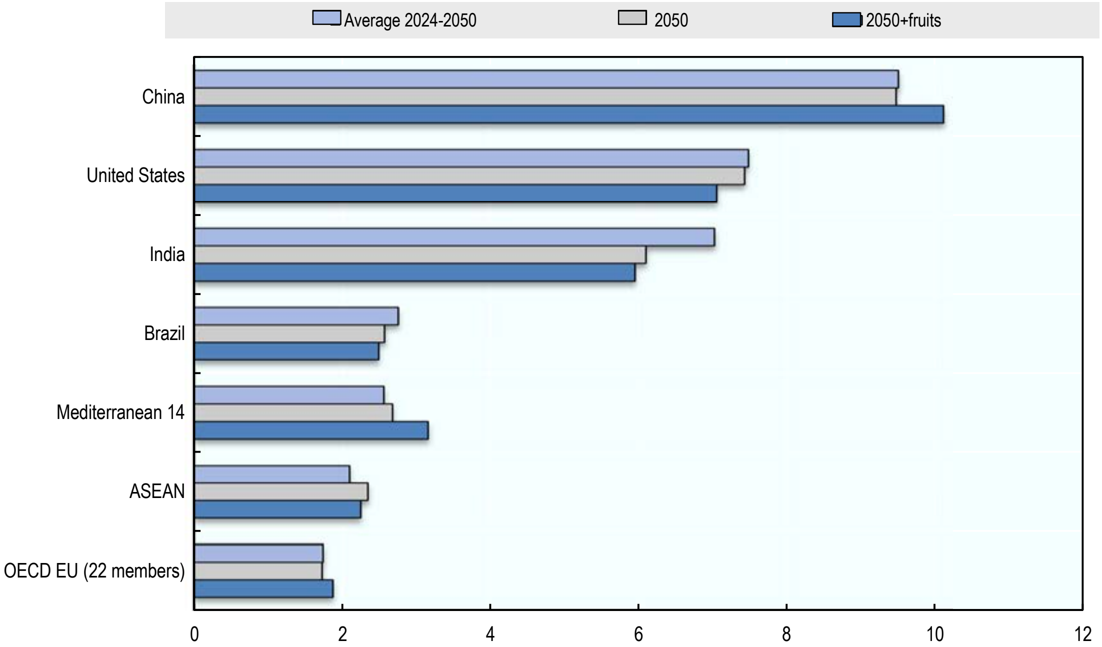
Brazil and the Mediterranean region as a whole may be considered secondary future water risk hotspots for agriculture production (Figures 2.7 and 2.8). Despite its low rank in water risk in Figure 2.5, Brazil is projected to remain a leading producer of multiple commodities. All 14 Mediterranean countries are identified among the countries most exposed to high water risks (Figure 2.5), but even combined together, they represent a much lower share of agriculture production than Brazil, thereby reaching similar scores on Figure 2.8. Focusing on national differences (Figure 2.7), Pakistan and Argentina also score high for agriculture water risks, as they combine large national agriculture productions and significant water risks.

Figure 2.7. Future agriculture water risk indices, top 15 countries



Source: Derived from the analysis of 64 publications, and AgLink-Cosimo and IMPACT projections.

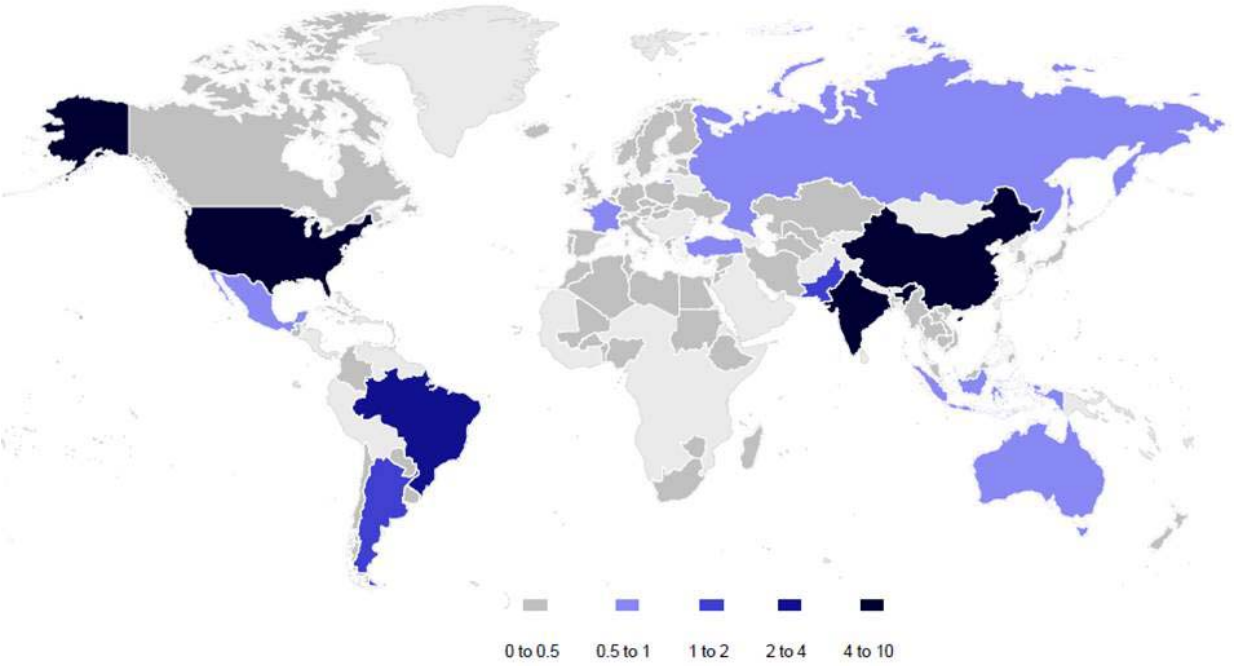
Figure 2.8. Future agriculture water risk indices for the leading four countries and for four regions facing high water risks



Note: Countries of the Mediterranean 14 region are: Morocco, Algeria, Tunisia, Libya, Egypt, Jordan, Israel, Lebanon, Syria, Turkey, Greece, Italy, France and Spain. For ASEAN, the represented countries are Myanmar, Cambodia, Lao PDR, Viet Nam, Thailand, Malaysia, the Philippines and Indonesia

Source: Compilations using AgLink-Cosimo and IMPACT projections and results from the review of 64 publications.

Figure 2.9. Future water risk hotspots in global agriculture production (2024-2050 average)



Note: The index can be interpreted as the expected share of overall global production of the key agriculture commodities likely to face high water risks without adaptation action in each of the 77 largest agriculture-producing countries.

Source: Review of 64 publications, AgLink-Cosimo and IMPACT simulations.

These rankings should not mask the importance of differences in water risks and agriculture activities. Figures 2.A2.2 and 2.A2.3 in Annex 2.A2 give a decomposition of the same indicators by the eight commodities plus fruit, using the IMPACT projections for 2050. It should be noted that these national level measurements may be inaccurate for large countries, where specific agriculture activities do not coincide with water risks. With this important limitation in mind, Table 2.3 shows the three leading countries for each commodity, together with high risk supranational regions and their hypothetical rankings. China, India and the United States are the leading countries in terms of production at risk under almost all categories based on these indicators, followed by Brazil and Indonesia as major producers of certain products. At the supranational level, Indonesia contributes to the higher rank of ASEAN for rice and oilseed production. At the same time, the fruit sector in Mediterranean countries is expected to face major water risks, and OECD EU countries as whole face significant water risks in some sectors.

Table 2.3. Countries leading in agriculture future water risk indicators in 2050

	Country-based	Regions with high risks (theoretical rank)
Beef	1. China (7.7), 2. United States (6.7), 3. Brazil (3.8)	
Dairy	1. India (14.8), 2. China (6.3), 3. United States (5.8)	4. OECD EU members (2.9)
Coarse grains	1. United States (20.0), 2. China (12.5), 3 Brazil (2.3)	4. OECD EU members (1,6)
Rice	1. China (16.5), 2. India (11.8), 3. Indonesia (1.8)	3. ASEAN (6.4)
Wheat	1. China (8.5), 2. United States (5.0), 3. India (4.1)	5. OECD EU members (2.9)
Sugar	1. Brazil (7.2), 2. India (5.4), 3. China (4.3)	5. OECD EU members (2.5)
Cotton	1. China (14.9), 2. United States (10.9), 3. India (5.3)	
Oilseeds	1. United States (7.0 2. Indonesia (5.5), 3. China (5.0)	1.ASEAN (8.9)
Fruits	1. China (15.2) 2. India (4.8), 3. United States (4.0)	2. 14 Mediterranean countries (7.0)

Source: Author's own work, derived from the combined analysis of water risks and agriculture regions. See full results in Annex 2.A2.

These three countries also dominate in the different classes of water risks. The disaggregated indicators are shown for the three leading countries at risk in Table 2.4. While all countries are expected to be subject to the risk of water shortages, excess water is reported to be more of a problem in parts of China and India than in the United States.

Table 2.4. Share of categorical indices of future water risk in the three hotspot countries

	China	India	United States
Shortage	73%	58%	71%
Excess	65%	65%	30%
Variability	50%	0%	75%
Quality	33%	67%	67%

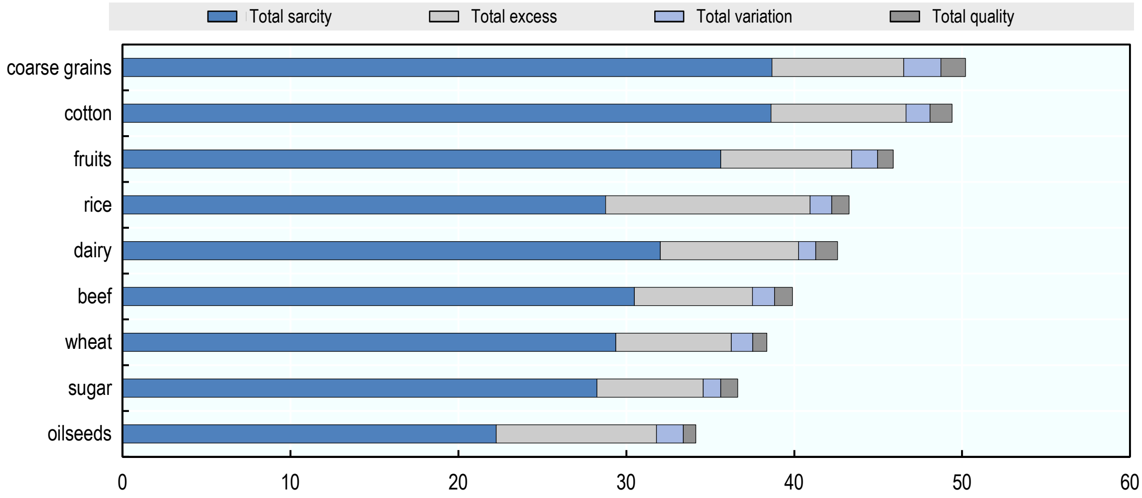
Source: Author's own work.

The combination of these two characterisations shows that different commodities will face different types of risks. Box 2.2 shows that coarse grains, cotton and fruits areas are found to be the most affected by water shortages.

Box 2.2. What type of water risks could affect specific agriculture commodities in 2050?

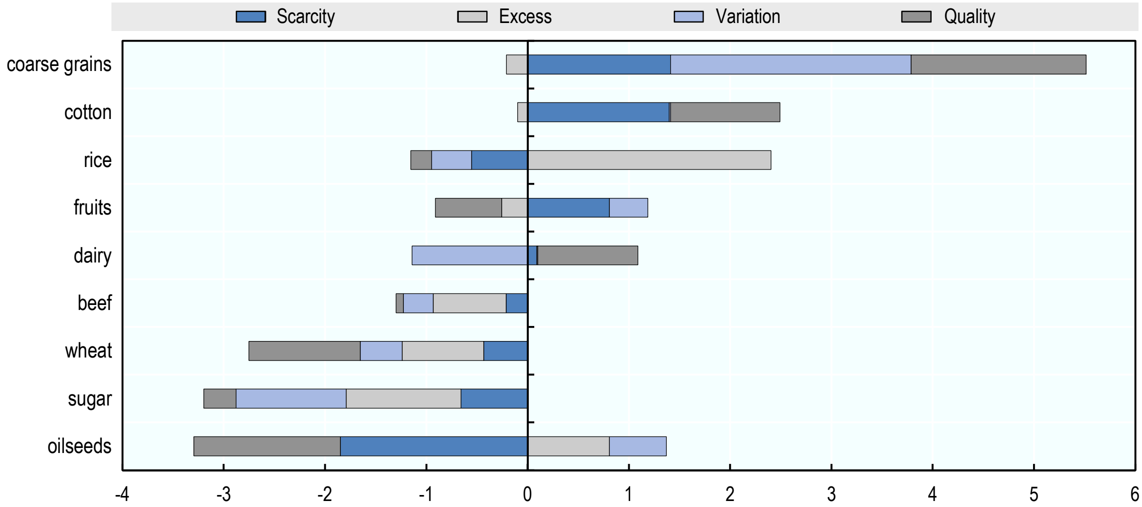
A broader question is what type of products may be most at risk. The indicators for future water risk for the 77 countries (and representing over 89% of global production of each commodity) can be used to derive commodity-based indicators for the entire market. The results (Figure 2.10) suggest that the areas most at risk are those that are projected to produce coarse grains, cotton, fruits, rice and dairy. Overall, these aggregate indicators suggest that 40% to 50% of global production of these commodities could face future water risks.

Figure 2.10. Aggregate future water risk indices (%) by commodity group in 2050



More specifically, Figure 2.11 shows the *relative* importance of the type of water risks in driving average future water risks by commodity, measured by computing standardised indices of changes. It shows that the risks of scarcity and extreme events (droughts) are especially important for countries that produce coarse grains, cotton and fruits (and relatively less oilseeds, sugar and wheat), while excessive water is projected to affect mostly rice and oilseed production areas (and less so sugar, beef, wheat or coarse grains). Water quality risks are projected to be more important in areas with coarse grains, cotton, and dairy, and lower in countries with oilseeds sugar and wheat.

Figure 2.11. Relative importance of the types of risks affecting commodity groups in 2050



Source: Compilations based on IMPACT projections and the review of 64 studies.

China, India and the United States are enormous in size, but not all subnational regions are identical in agriculture production activities, nor subject to the same future water risks. Ideally, a full representation of subnational hotspots would require a complete global assessment of subnational water risks and commodity importance. Several reviewed studies did integrate water risks with agriculture, but they often focused on a single dimension of risks, and used specific scenarios and models that also face limitations.[12]

The following sections look at agriculture regions facing high water risks within each identified hotspot country. This second step considers national level risks, but nonetheless aims at targeting significant regional agriculture water risk, as the regions are selected based on the same criteria in countries that concentrate global agriculture production and water risks.

2.4. High agriculture water risks for agriculture in Northeast China, Northwest India and the Southwest United States

Identifying regions with high agriculture water risks in the three countries

The literature review undertaken can help single out regions that are most at risk in the three hotspot countries. Table 2.5 shows the frequency of reported water risks in specific regions. Combined with information about major agriculture production area, the following three regions are identified.[13]

- In China, most reported observations (48) locate prevalent water risks in the semi-arid northeast, which is the largest agriculture production region for cereals and cotton. It is also a largely populated and industrial economic region, with high levels of competition for water, and intense groundwater depletion.
- In India, several studies project high water risks throughout the country, with most observations (53%) pointing towards the cereal producing regions of the north and especially the northwest. and others (35% of the observations) reporting flooding or drought risks in the south-east, which has more diverse types of agriculture. Northwest India is known as the breadbasket of India and one of the world's hotspot for groundwater depletion due to intensive irrigation (e.g. Taylor et al., 2013).

Based on these criteria it is expected to be one of the most important agriculture regions facing water risks in India and worldwide.

- In the United States, the Southwest region is facing the most water risks, with 46 observations. Multiple studies have shown that this water stressed region is at risk of increased water constraints (e.g. Cook et al., 2015). The region includes California, the leading US state in overall agriculture revenues, and the largest US state in terms of dairy production, vegetable and fruits, a large cattle producer, and a major exporter of agriculture commodities (Cooley et al., 2016).

Table 2.5. Three regions stand out from the water risk assessment

	United States*	China	India
Central	23%	2%	9%
Northwest	19%	27%	**53%**
Northeast	9%	**59%**	39%
Southwest	**58%**	13%	32%
Southeast	15%	18%	35%

Note: *4% also identified Alaska and 11% Texas. Only observations with regional differences are accounted for. Current and future risks are pooled.
Source: Author's own derivations based on the reviewed literature.

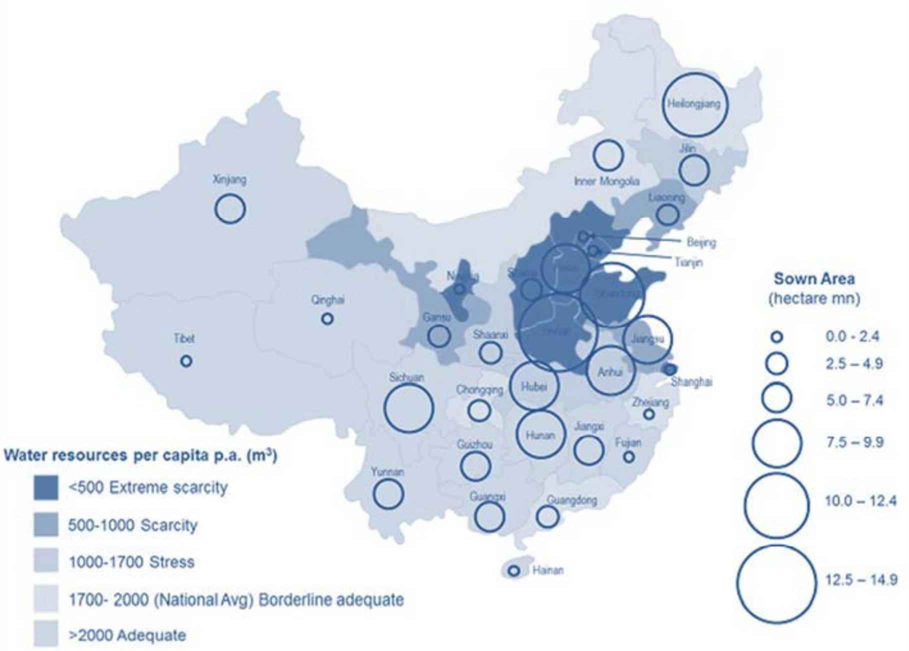
The rest of this chapter will focus on these three key regions, analysing their agriculture and water risk specificities. While the present assessment cannot confirm their standing in comparison with subnational regions in other countries, collected literature-based evidence reviewed in this report does suggest their high concentration of water risks and agriculture production even at the global level. These three national hotspot regions also represent different agriculture structure and levels of development, providing a good basis to study more specifically how water risks can impact productive agriculture regions.[14]

Similar water trends across the three regions

The three regions face a number of similarities: a diverse agriculture production, increasing shortages of usable groundwater, and unstable surface water levels unstable given the pressure from other sectors.

Although characterised by extreme water scarcity (Figure 2.12), Northeast China[15] is a key area for agriculture production, industry development and population growth. National statistics show that in 2013, this region accounted for about 25% of wheat, corn and cotton, and 10% of rice and apple total production. With 8% of China's total water resources and one-third of China's population and GDP, competition for water resources is high (Liu and Speed, 2009). This incongruity has increased in recent decades due to declining water supply, lower precipitation, deteriorating water quality, and rising water demand (Hijoka et al., 2014; Box 2.3).

Figure 2.12. Northeast China concentrates agriculture and water scarcity

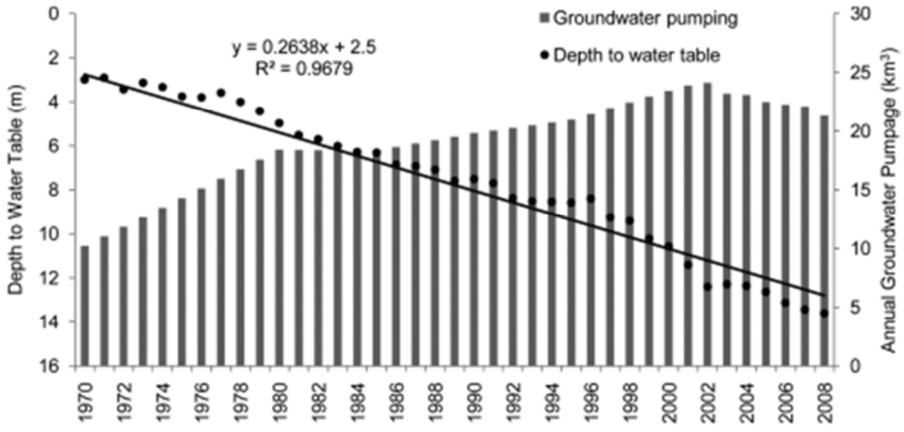


Source: Tan (2014). http://chinawaterrisk.org/resources/analysis-reviews/the-state-of-chinas-agriculture/.

Box 2.3. Factors that have increased water risks in Northeast China

The increasing frequency of more severe droughts, as well as the generally declining level of average precipitation from 1960 to the early 2000s, have considerably limited the *water supply* in Northeast China (Piao et al., 2010). Although the estimated level of water resources in the Northeast has stabilised (Figure 2.A2.5 in Annex 2.A2), the decrease in the groundwater level in the North China Plain — an agriculturally important sub-region of the Northeast — by about 1m per year over the last 20 years (Figure 2.13) is of critical concern (Foster and Garduño, 2014; Kendy et al., 2003; Chen, 2010, Giordano, 2009, Zhang and Diaz, 2014). This phenomenon, largely driven by intensive pumping for irrigation (Cao et al., 2013), has generated flow cut-offs from the Yellow River and its tributaries, and has contributed to the disappearance of 194 natural lakes and 40% of the region's waterways, in addition to allowing for coastal seawater intrusion and land subsidence in certain areas (Jiang, 2009; Moore, 2013; Sun et al., 2010; Wang and Jin, 2006; Wang et al., 2007).

Figure 2.13. Average levels of groundwater pumping and water tables in the North China Plain



Note: Water tables were simulated based on best available information. Annual groundwater pumping before 1980 is estimated.

Source: Cao et al. (2013).

Water quality issues are also exacerbating water stress for agriculture in the Northeast. Water quality in the Yellow River declined steadily from 1985 to 2001 (Giordano, et al., 2004, see Figure 2.A2.6 in Annex 2.A2). Water in Classes IV and V – which is only suitable for industrial or agriculture use – increased from 4% in 1985 to 25% in 2001. One-third of the studied Yellow River water was deemed unfit even for agriculture in 2007 (Branigan, 2008). Although water quality of the Yellow river has reportedly improved in recent years, the quality of other rivers in the Northeast – such as the Huai and Liao – have declined (China Water Risk, 2015). Furthermore, 70% of the rural North China Plain's groundwater is too polluted at present for human use and could be harmful for agriculture (China Water Risk, 2016.)

Rising water demand is also a factor in water stress. In line with national trends, the agriculture sector is the largest water user in the Northeast (Figure 2.A2.5 in Annex 2.A2). In contrast to the 8% increase in agriculture use at the national level, agriculture use in the Northeast remained relatively steady from 2004 to 2014. During the same period, use by other sectors increased 20% in the Northeast, but only 13% at the national level. Increased production of relatively water-intensive crops such as corn – and higher transpiration rates due to excessive fertiliser use – have also reduced the water content of topsoil in Northern China (Liu et al., 2015).

Lastly, water stress in Northeast China has been compounded by *inefficient water usage*. The effective utilisation ratio of water (water effectively used over water withdrawn) in Chinese agriculture has improved from 44% in 2002 to 52% in 2013, but remains approximately 20 percentage points below the ratio in developed countries (Yu, 2016). Producing 1 kg of grain in China requires twice the water needed in developed countries (0.96 m^3) (Zhao et al., 2008). This is partly due to China's open channel irrigation system, which is highly susceptible to leakages. Water inefficiency may be particularly high in the Northeast due to low precipitation levels and a higher reliance on irrigation. Only a fraction of irrigated land in Northeast China is equipped with water-saving irrigation technologies (Huang et al., 2017).

Source: Branigan (2008); Cao et al. (2013); Chen (2010); China Water Risk (2015), Foster and Garduño (2004); Giordano (2009); Giordano et al. (2004); Huang et al. (2017); Kendy et al. (2003); Liu et al. (2015); Piao et al. (2010); Yu (2016); Zhang and Diaz (2014); Zhao et al. (2008).

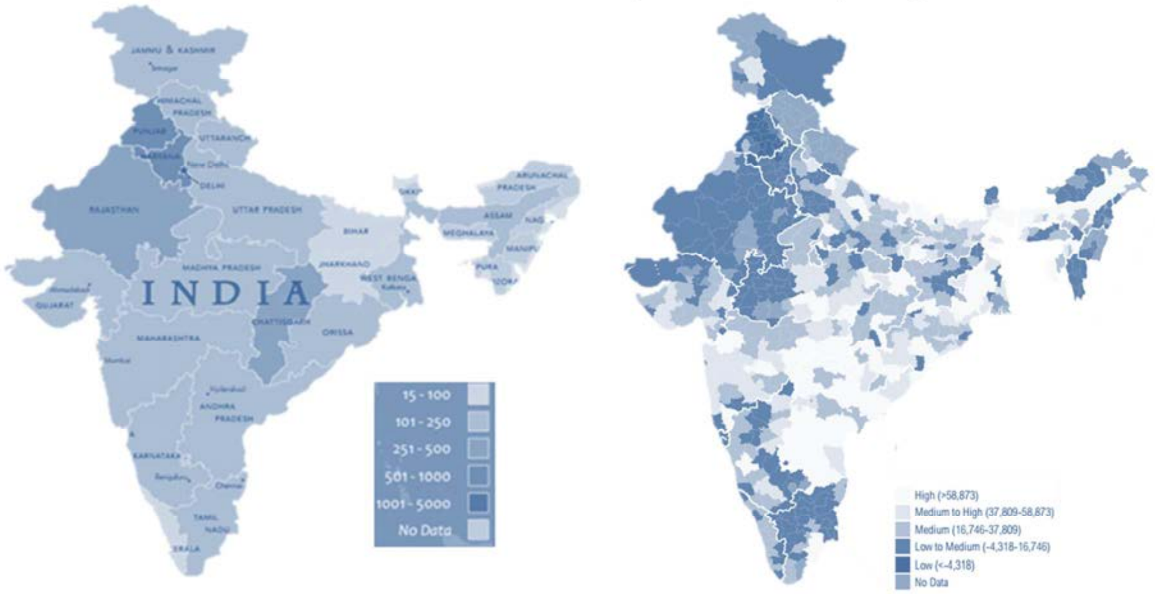
The negative impact of water stress on agriculture production can already be seen for water-sensitive crops in drought years. For instance, corn production declined in the droughts of 1997, 1999, 2000, 2009 and 2014. Wheat production also declined in several years following droughts; sharp decreases can be found in 1998, 2000-2003; a slowdown also occurred in 2007 and 2009-2010.

Recent shifts in the Northeast's production basket do not appear to have reduced the region's water demands; overall production has increased, though its composition has evolved. Shares of corn and apple production have increased from 2004 to 2013 (Figure 2.A2.7 in Annex 2.A2). At the same time, production has shifted away – in relative terms – from cotton, rice, beans and tubers (and wheat to a certain extent). Taking into account the water requirements of these crops, water stress may have been reduced by the relative decline in cotton, rice and bean production and relative increase in apple production in recent years. However, it is unclear whether rising production of corn – a relatively water-intensive crop – may have offset this gain.

At the interface between the Indus and the Ganges river basins, Northwest India, here defined by the states of Punjab and Haryana, is the breadbasket of the country (Figure 2.14 left panel). These states belong to the Indo-Gangetic Belt, a fertile region with important groundwater and surface water resources, supplied by the snowmelt water of the Himalaya and annual monsoon rains. However, the climate is characterised by high inter-seasonal and inter-annual variability in precipitation, which makes them particularly exposed to drought (Punjab Department of Revenue, Rehabilitation and Disaster Management, 2014). Total water availability in Punjab is estimated at 39.5 km3 (32 Million acre-feet), while demand—largely borne by the agriculture sector—reaches 61.7km3 (50 Million acre-feet) (Punjab Department of Irrigation, 2008). This 38% deficit puts water reserves under pressure and causes groundwater depletion at a rapid pace. Haryana faces the same problem as Punjab: a rising gap between water demand and supply, which puts into question its capacity to sustain its large agriculture sector if water consumption does not become drastically more efficient.

Figure 2.14. A key grain production region under increasing groundwater stress

Food grain production 2010-2011 (tonnes/capita), Net groundwater availability for irrigation in 2025



Source: Iyer (2013), https://www.scribd.com/document/202944804/Food-An-Atlas ; Shiao et al. (2015), http://www.wri.org/resources/maps/india-water-tool

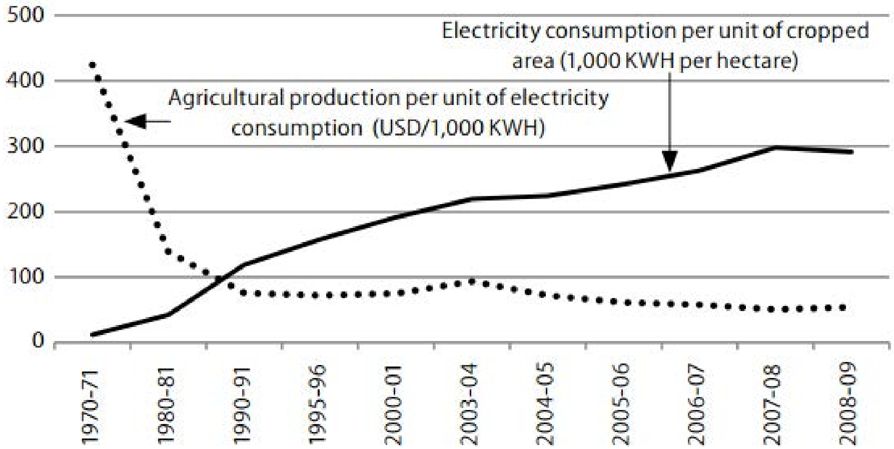
Agriculture in this region depends on groundwater irrigation. To respond to a dry climate, the quasi totality of the cropped area in Punjab and Haryana is irrigated. Irrigation development and the use of high yielding seed varieties that are sensitive to drought have been encouraged since the Green Revolution (Murgai, 2001). Double cropping, first during the monsoon and then during the dry season, further increases the need for water input (Ministry of Statistics and Program Implementation, 2016a; Indian National Informatics Centre, 2016a). Groundwater irrigation expanded rapidly from the 1960s, pushed by affordable private tube well extraction systems—particularly suited to fragmented landholding (Banerji et al. 2010; World Bank, 2013b)[16]—, by government programmes encouraging intensive rice and wheat cultivation, and later by rural electricity subsidies (Box 2.4). It gradually replaced the use of a large but outdated canal network.[17] At present, respectively 53% and 71% of the sown area in Haryana and Punjab is under tube well irrigation. In comparison, only 21% of the sown lands are under tube well irrigation countrywide (Ministry of Statistics and Program Implementation, 2016b).

Box 2.4 Productive agriculture at the cost of depleting aquifers: The role of policies

From 1960 to 2009, the cropping intensity in Punjab rose from 126% to 190%, and the very water-intensive rice-wheat rotation covered the majority of the area (80% of cropped area), in part due to agriculture price policies. The area under paddy cultivation is about 2.8 million hectares in Punjab, while groundwater recharge capacity can only sustain 1.6 million hectares, leading to the continuous lowering of water table levels (CFAPPS, 2013). Farmers are incentivised to grow rice and wheat since food grain prices are guaranteed by the government, and their yields vary less than for other crops (Singh, J., 2013). Minimum support prices for these two crops also strongly limit potential crop diversification, necessary for a transition toward a less water-intensive agriculture (Garduño et al., 2011). Recent diversification efforts in Punjab are targeting shifts mainly to maize, cotton, sugarcane, and basmati rice, which need less water than Indica rice, the predominant variety (CFAPPS, 2013).

State subsidies for irrigation, in the form of energy subsidies, is a central factor explaining groundwater demand and overdraft in Punjab and Haryana. Whereas a falling water table level increases the amount of energy needed to lift water, this rising cost is not directly born by the farmers, who benefit from a free power supply (Badiani et al., 2012; CFAPPS, 2013). Therefore, there are few incentives to experiment less water-consuming cropping methods or to invest in water-saving technologies, even if growing cereals is increasingly energy-costly (Sharma et al., 2015) (Figure 2.15). In 2003, electricity subsidies to agriculture weighed 7.36% of Punjab state expenditures, which was more than the state budget allocated to health and education together (Birner et al., 2011). As of 2016, they still represented 6.8% of the State budget (Krar, 2016). In Haryana, where the farming sector consumes 40% of electrical power, the State decided to pursue and extend power subsidies to farmers. Thus, the allotted amount per cropped area rose by 42% between 2010 and 2014, in spite of heavy budget difficulties (Kumar et al., 2011; *The Times of India*, June 2014).

Figure 2.15. Energy efficiency and agriculture growth in Punjab



Source: Sarkar and Das (2014).

Power restrictions, instituted for energy control, have deferred the evolution of agriculture practices. Free energy supply for irrigation purposes is also made at the expense of the maintenance of the electricity network, which frequently collapses. As a result, farmers have installed automatic power switches to pump water as soon as power is available. This uncontrolled and unmetered irrigation system encourages excessive water extraction (Planning commission, 2009). In order to limit the use of water pumps, the State authorities determine pre-announced restricted hours during which free power will be available for irrigation. In Haryana, farms receive power six to ten hours a day, distributed in several phases (World Bank, 2001). In Punjab, power is available from four to eight hours a day (Sarkar and Das, 2014). These conditions are not adapted to drip irrigation, which requires a continuous power supply for at least eight hours (Punjab Department of Soil and Water Conservation, 2016). Therefore field flooding, which has very low water use efficiency, remains the most commonly used irrigation technique.

1. Cropping intensity can be defined as "the fraction of the cultivated area that is harvested. [It] may exceed 100 percent where more than one crop cycle is permitted each year on the same area." See www.fao.org/nr/water/aquastat/data/glossary/search.html?termId=7587&submitBtn=s&cls=yes

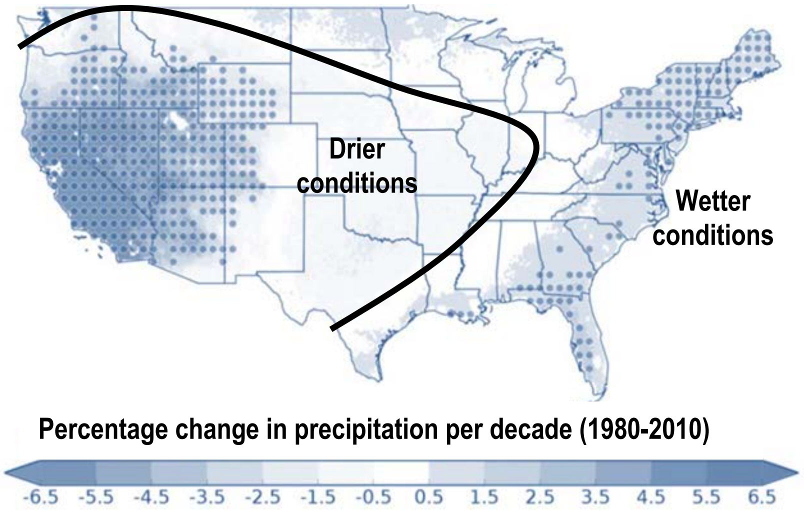
Source: Badiani et al. (2012); Birner et al. (2011); CFAPPS (2013); Garduño et al. (2011); Krar (2016); Kumar et al. (2011); Planning Commission (2009); Punjab Department of Soil and Water Conservation (2016); Sarkar and Das (2014); Singh (2013); World Bank (2001).

The rapid development of groundwater irrigation has broadly contributed to the productivity gains of Indian agriculture during the Green Revolution, but the continuous rise of tube well irrigation has led to an overexploitation of water reserves (Venkata and Burke, 2013) (Figure 2.14 right). In the beginning of the 2000s, groundwater consumption started overwhelming the recharge capacity in the States of Haryana and Punjab (Gandhi and Namboodiri, 2009). Ten years later, despite the growing awareness of central authorities, the tendency has dramatically intensified: in 2011, groundwater development stress[18] reached an average of 133% in Haryana, 172% in Punjab, and up to 416% in some districts (CGWB, 2014). In 2010 water level fell beyond a depth of 15m in 75% of Punjab, a significant increase from 2000 and 1980 when 14% and 0.6% of the area fell under this level (CFAPPS, 2013) (Figure 2.A2.10 in Annex 2.A2). As of 2016, 51% of the local administrative units called blocks[19] in Haryana and 75% of the blocks in Punjab are considered as over-exploited (CGWB, 2016). This phenomenon has been confirmed by satellite gravity data measurements that showed a rapid depletion of groundwater from 2002-2008 (Rodell, 2009). Groundwater depletion has also contributed to exacerbating water quality concerns (MacDonald et al., 2016).[20]

The Southwest United States[21] —defined here as Arizona, California, Colorado, Nevada, New Mexico, and Utah (six bottom left states on Figure 2.16)—is a rapidly growing important agriculture region that faces major water challenges. It has the fastest-growing population and one of the most economically important regions of the United States. It is also the nation's most arid region and increasingly prone to long-term droughts (Prein et al., 2016). The region is among the most productive agriculture regions in the world, generating 17% of national agriculture sales (BEA, 2015), and leading in US production and exports of many agriculture products. Agriculture in this region largely relies on irrigation and the sector contributes to an overuse of water resources, as observed by the rapid depletion of groundwater in the Central Valley of California (4.8 km^3 per year, Famiglietti et al., 2011) and the irregular flow of the Colorado River, which in the last 50 years has rarely reached the sea.

Recent trends show that agriculture has reduced its water use. While agriculture still accounts for about 70% of total freshwater withdrawal, water withdrawals declined from 1990 to 2010 by 18% across the region (Maupin et al., 2014). Between 2003 and 2013, total irrigated land declined by 6% in the Southwest, irrigated pastureland decreased by 11%, and rainfed pastureland increased by 25%. These changes may have been responses to the persistent drought conditions and the overall diminution of precipitations, as observed in Figure 2.16, or to long-term market trends.

Figure 2.16. Weather patterns that bring rains are increasingly rare in Southwestern United States



Note: This map depicts the portion of overall changes in precipitation across the United States that can be attributed to these changes in weather system frequency. The line delimits areas with negative change in precipitation (drier conditions) from those with positive precipitation change (wetter conditions). The grey dots represent areas where the results are statistically significant.
Source: Prein et al. (2016). https://www2.ucar.edu/atmosnews/news/19173/southwest-dries-wet-weather-systems-become-more-rare

Despite declines in water reserves, agriculture sales in the region increased by nearly 28% between 2005 and 2014, driven largely by California crop production, particularly fruits and nuts. The Southwest region doubled its agriculture exports over the same period. Much of this growth can be attributed to increased exports of meat and dairy products. The value of beef and veal exports, for example, increased nearly five-fold over the last decade, and the value of dairy exports tripled. Since 2005, the export value of crop products has increased by about 86 per cent.

These seemingly counter trends suggest that the agriculture sector has shown remarkable adaptability and resilience to droughts. Yet recent developments suggest this increase may not be sustainable. The 2011-16 drought in California encouraged the intensification of groundwater irrigation, leading to the accelerated depletion of the Central Valley aquifer as well as generating large negative external problems (Phillips et al., 2015).[22] The observed shift in farming from field crops to higher value permanent crops (fruits and nuts) may also have reduced the farming sector's adaptability to drought.

Growing water risks expected in the future

Although projections are subject to uncertainty, agriculture water stress in Northeast China is likely to worsen overall due to a combination of factors (see Annex 2.A2.3 for details).

- Climate change is projected to raise temperatures, leading to increased evaporation and to the melting of critical glaciers. The projected impact is mixed and uncertain on regional precipitation. The former suggests that short-term surface water scarcity relief could be accompanied by long-term, seemingly irreversible, water scarcity challenges (NARCC, 2007; Piao et al., 2010; Tao et al., 2003; Thomson et al., 2006; Zhang et al., 2007).

- Demand for water will continue to increase due to China's continued economic development, population growth and urbanisation dominating the overall water balance (2030 WRG, 2009). The largest supply-demand water deficit in 2030 (39%) is expected to be found in this region (Hai Basin, see 2030 WRG, 2012). Water demand in China's Northeast is predicted to increase across all sectors, with agriculture losing shares to other sectors (e.g. Table 2.A2.2 in Annex 2.A2).
- Despite a projected increase in recharge, groundwater in the North China Plain is projected to continue to be under pressure (Cao et al., 2013; Döll and Fiedler, 2008; FAO and WWC, 2015; Taylor et al., 2013).
- As industry expands, surface and groundwater quality is expected to further deteriorate due to rising pollution levels which will reduce the availability of usable water for agriculture (World Bank, 2013a; China Water Risk, 2016).

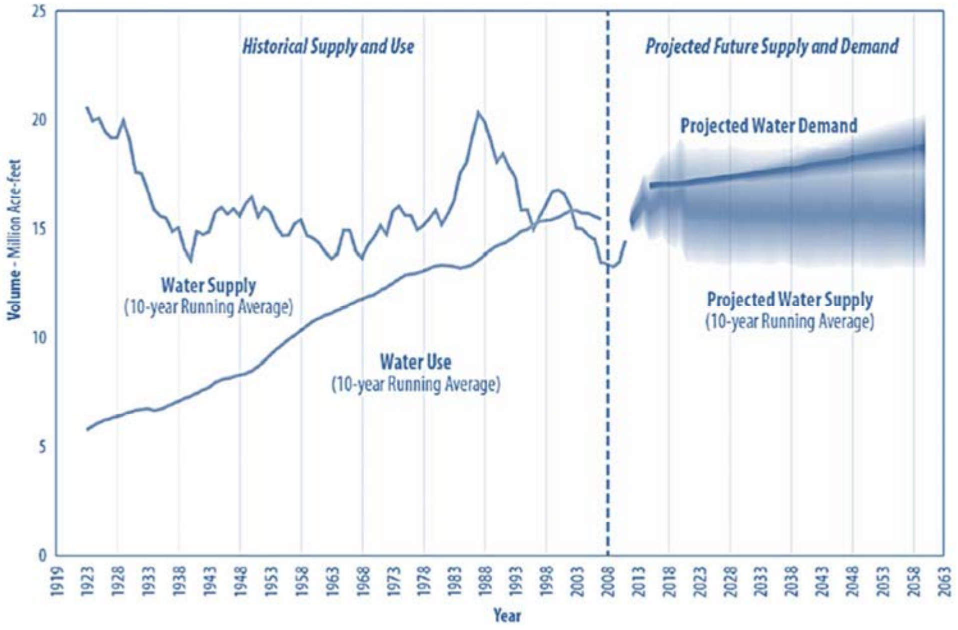
Northwest India is expected to face a higher water supply-demand gap, increased inter-seasonal rainwater variability, and potential deterioration of surface and groundwater quality (see details in Annex 2.A2.3). Water demand will increase, pushed by non-farming demand; in the next ten years, the region's population will increase by 5.8 million, and the urban population by 43% (National Commission on Population, 2006). By 2025, Punjab projects a 38% increase of domestic and industrial groundwater consumption, as compared to 2011 (CGWB, 2014). Climate change is expected to increase rainfall variability, leading to floods during the monsoon (Döll, 2002; IPCC, 2008), lower surface water supply and groundwater recharge and potential increase in irrigation water demand, exacerbating the pressure on aquifers (Bruinsma, 2003; Krishan et al., 2015; Mohinder, 2016; Taylor et al., 2013). Northwest India is projected to be one of the only Indian regions where groundwater levels are expected to decrease at a faster rate with climate change and irrigation requirements (Zaveri et al., 2016). The intensive exploitation of aquifers is expected to worsen groundwater quality, potentially reducing its availability for agriculture. Saline intrusion in groundwater, already expanding in Punjab, is expected to increase (Hill-Clarvis et al., 2016; Kim, 2013; Mahajan, et al., 2012), potentially affecting surface water (BGS, 2015). Growing industrialisation may also impact surface and groundwater usability.

The Southwest United States will also have to cope with more variable and uncertain water supplies due to the combination of lower and more volatile water supplies in critical river basins and projected higher demand. Climate change is projected to exacerbate the demand supply gap in the Colorado River Basin (USBR, 2012) (Box 2.5). Annual runoff in the northern part of the California Central Valley is projected to show little or no change, while some drying is projected in the southern portions of the region (USBR, 2014). Warmer temperatures during the winter months, however, cause precipitation to fall as rain rather than snow, increasing winter run-off and reducing spring run-off, which will reduce the ability of the state to store water in reservoirs (Ibid.).[23] Continued population growth may put additional pressure on the region's limited water resources; by 2030, an additional 23 million people are expected to live in the region bringing the area's population to 73 million, 48% higher than in 2000 (United States Census Bureau, 2005).

Box 2.5. Projecting water risks: The Colorado Basin

The Colorado River has played an important role in the development of the US Southwest and parts of northwestern Mexico, supplying water to about 40 million people in both countries, and wholly or partially irrigating more than 2 million ha inside and outside of the basin. A dense yet dynamic set of regulations, interstate compacts, agreements, contracts, judicial decisions, and an international treaty, known collectively as the "Law of the River", governs the allocation and use of water from the Colorado River water within the United States and from the United States to Mexico. Although massive dams along the river's main stream and many of its tributaries can store as much as four times the Colorado River's average annual flow, these have devastated ecosystems and driven several native fish species to the brink of extinction. These institutional and structural controls severely constrain the river's natural variability and significantly reduce the volume of water flowing to the border. In the past several decades, the Colorado has rarely had enough water to reach the sea.

Figure 2.17. Historical and projected Colorado River Basin water use and demand



Note: Water use and demand include Mexico's allotment and losses, e.g. those due to reservoir evaporation, native vegetation, and operational inefficiencies.

Source: USBR (2012).

Beginning in 2010, the US Bureau of Reclamation partnered with Colorado River Basin stakeholders to evaluate future water supply and demand in the basin through the year 2060 and develop mitigation and adaptation strategies to address water supply and demand imbalances. The Colorado River Basin Study (USBR, 2012) was finalised in 2012 and included four future water supply scenarios to help capture the range of potential futures and reflect the uncertainty of projecting water supply in a highly variable system. In the 100-year historic record, mean annual runoff at Lee's Ferry – the traditional measuring point for the Colorado River - has been about 18 km3, with more than 80% of the runoff generated from about 15% of the Colorado River Basin at elevations exceeding 2 400 meters. The climate change scenario projects a general drying trend in the basin, with the notable exception of increased precipitation in the higher elevation, productive headwaters regions. With climate change, total runoff was projected to decline by 9.1%, with greater annual and monthly hydrologic variability in an already dynamic system, reducing predictability and reliability for water managers. The other water supply scenarios, based on the 100-year historic record and the much longer tree-ring record, projected that runoff would decrease by less than this amount. As shown in Figure 2.17, supply and demand imbalances already exist in the Colorado Basin and are projected to become more severe in the future.

Source: USBR (2012).

Notes

1. The hotspot approach as defined here includes both the hotspot identification exercise and the targeted response. Annex 2.A1 provides a methodological note with a discussion on water risk definitions.

2. Targeting water risks may also result in neglecting other types of risks for agriculture. The current approach does not claim to respond to all agriculture problems.

3. It should be noted that the approaches presented here focus mainly on the benefits of risk mitigation and not cost mitigation. In other words, targeting water risks for agriculture will not focus on whether low-cost solutions exist, but rather where the most critical risks may lie. This does not prevent considering cost-effective solutions to these problems.

4. For instance, a key objective of the OECD Council Recommendation on Water (OECD, 2016b) is "The application of pollution control measure as close to the source as possible".

5. If the studies are done at the global level, they may not always cover all countries thoroughly.

6. A secondary step is taken by identifying agriculture production regions facing water risks within each of the identified countries in section 2.4.

7. The overall methodology and list of countries are available in Annex 2.A2. It includes OECD country results.

8. Many countries in sub-Saharan Africa are not found to be expected to face higher water risk in the reviewed literature. As noted above, this may reflect the fact that many of the climate projections do not foresee increasing risks in these regions compared to others, and some see water risks actually diminishing, even if they start from a higher risk level.

9. If these three countries are large, the fact that other large or larger countries do not feature in this list, such as Brazil, Canada or the Russian Federation, but that small countries like Lebanon or Kuwait do, shows that the scale bias is not predominant with this method.

10. This asymmetry may be due to uncertainties of projections. One could expect less consistent estimates in the future than current measures, and the fact that there are fewer data points for current than future risks may create a bias.

11. This was done by aggregating their agriculture water risk indices for each region.

12. Researchers at the World Resource Institute have developed a mapping tool to indicate agriculture's exposure to water stress by agriculture commodity, but the analysis used recent or current data, without projecting future risks. http://wri.org/applications/maps/agriculturemap/#x=0.00&y=-0.00&l=2&v=home&d=rice

13. There was no sufficient data and publications to conduct a similar quantitative assessment of water risks and subnational agriculture projections in the three countries, but the review of literature conducted in each region (presented in following subsections) concurs with this selection.

14. Interestingly, the regions found to be most at risks are also significant agriculture regions. The link between the importance agriculture production and water risks can be partially explained by climatic and other non-water risk-related factors, including the quality of the land, rural development, etc.

15. For this analysis, data is drawn from ten provinces in Northeast China classified with extreme water scarcity: Beijing, Gansu, Hebei, Henan, Jiangsu, Liaoning, Ningxia, Shandong, Shanxi and Tianjin (Tan, 2014).The region includes four main rivers: the Huang (Yellow), Huai, Hai and Liao rivers. The Yellow River is the second longest river in China and its river basin connects to the Hai and Huai rivers.

16. A tubewell in Punjab irrigates 2.8 hectares of crops in average, but when considering small holdings (1 to 2 ha) one tubewell provides water to only 1.2 hectares (Indian National Informatics Centre, 2016b).

17. The two states are also in conflicts with regards to the sharing of river waters mostly for canal irrigation (Mangat, 2016).

18. Groundwater development stress is defined as the current annual rate of groundwater abstraction divided by the mean annual natural groundwater recharge.

19. Blocks are the assessment units used by the Central Groundwater Board to follow local water level trends. Punjab counts 138 blocks, and Haryana 108.

20. Within 60% of the aquifer under the Indo-Gangetic Basin, potable water is limited due to arsenic or excessive salinity (MacDonald et al., 2016).

21. This section is based on Cooley et al. (2016). It should be noted that the Southwest Region defined here excludes the Central and Southern High Plains Aquifer region, where agriculture also faces high water stresses and where water demand exceeds supply (OECD, 2015a).

22. California passed its first legislation of groundwater in 2014 (Box 4.3 in Chapter 4), but the implementation of the law is projected to take until 2042.

23. Under current reservoir operating criteria, “with earlier runoff and more precipitation occurring as rainfall, reservoirs may fill earlier and excess runoff may have to be released downstream to ensure adequate capacity for flood control purposes”. (USBR, 2014: 4).

References

ADRC (Asian Disaster Reduction Centre) (2016), Global Identification number (GLIDE) database of international disasters, consulted December 2015, http://gs.adrc.asia/glide/public/search/search.jsp

Alavian, V. et al. (2009). "Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions", the World Bank, Washington DC.

Alcamo, J. et al. (2007), "Future long-term changes in global water resources driven by socio-economic and climatic changes", *Hydrological Sciences Journal*, Vol. 52/2, pp. 247–275. doi:10.1623/hysj.52.2.247.

Amarasinghe, U.A. et al. (2008), "India's Water Supply and Demand from 2025-2050: Business-as-usual Scenario and Issues", International Water Management Institute (IWMI), Colombo, Sri Lanka.

Arnell, N. W. (2004), "Climate change and global water resources: SRES emissions and socio-economic scenarios", *Global Environmental Change*, Vol. 14, pp. 31–52. doi:10.1016/j.gloenvcha.2003.10.006.

Aulakh, M.S. et al. (2009), ‘‘Water Pollution Related to Agricultural, Industrial, and Urban Activities, and its Effects on the Food Chain: Case Studies from Punjab", *Journal of New Seeds*, Vol. 2, pp. 112-137.

Badiani, R. et al. (2012) "Development and the Environment: The Implications of Agricultural Electricity Subsidies in India", *Journal of Environment and Development*, Vol. 21/2, pp.244–262.

Baettig, M.B., et al. (2007), "A climate change index", *Geophysical Research Letters*, Vol. 34, p. L01705.

Banerji, A. et al. (2010), "Social Contracts, Market and Efficiency: Groundwater Irrigation in North India", Working Paper No. 183, Centre for Development Economics, Delhi School of Economics.

Barnett, T.P. et al. (2005), "Potential impacts of warming climate on water-availability in snow-dominated regions", *Nature*, Vol. 438/17, pp.303-309.

Bates, B.C., et al. (eds.) (2008), "Climate Change and Water", Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

BEA (Bureau of Economic Analysis) (2015). "Regional Economic Accounts: SA45 Farm Income and Expenses", US Department of Commerce, Washington DC.

Bennett, B. (1998), "Rising salt, a test of tactics and techniques", *ECOS*, Vol. 96, pp. 10-13.

Bhupal, D.S. (2012), "Agricultural profile of Haryana", Agricultural Economics Research Center, University of Delhi, November 2012.

Bijlsma et al. (1996), "Coastal zones and small islands. In: Watson, R.T. et al. (eds.) *Climate Change 1995—Impacts*, *Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses,* Cambridge University Press, Cambridge, UK, pp. 289–324.

Birner, R. et al. (2011), "The Political Economy of Agricultural Policy Reform in India - Fertilizers and Electricity for Irrigation", IFPRI Research Monograph, International Food Policy Research Institute, Washington DC.

Brackenridge, G.R. (2016) "Global Active Archive of Large Flood Events", Dartmouth Flood Observatory, University of Colorado, Boulder, CO. Consulted January 2016. http://floodobservatory.colorado.edu/Archives/index.html

Branigan, T. (2008), "One-third of China's Yellow river 'unfit for drinking or agriculture'", *The Guardian*, London. http://www.theguardian.com/environment/2008/nov/25/water-china

Brauman, K. A. et al. (2015), "Water depletion : An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments", *Elemental: Science of the Anthropocene*, Vol. 4/83, pp.1–12. http://doi.org/10.12952/journal.elementa.000083

BGS (British Geological Survey) (2015), "Groundwater resources in the Indo-Gangetic Basin - Resilience to climate change and abstraction", British Geological Survey Open Report, Natural Environment Research Council, 31 July 2015.

Bruinsma, J. (2003), "World agriculture: Towards 2015/2030 – An FAO Perspective", FAO, Earthscan Publications Ltd, London.

Buckle, S. and F. Mactavish (2013), "The changing water cycle", Grantham Briefing Note 5, University College of London, London.

Buckley, C (2015), "The Findings of China's Climate Change Report", *The New York Times*, November 30, 2015.

Cao, G. et al. (2013), "Use of flow modelling to assess sustainability of groundwater resources in the North China Plain", *Water Resource Research*, Vol. 49, pp. 159–175

CCA (Council of Canadian Academies) (2013), "Water and Agriculture in Canada: Towards Sustainable Management of Water Resources", CCA, Ottawa, Canada. http://www.scienceadvice.ca/en/assessments/completed/water-agri.aspx

CCAFS (CGIAR Research Program on Climate Change, Agriculture and Food Security) and CIMMYT (International Maize and Wheat Improvement Centre) (2014), "Climate-Smart Villages in Haryana, India", Research Program on Climate Change, Agriculture and Food Security, New Delhi. https://cgspace.cgiar.org/rest/bitstreams/34314/retrieve

CFAPPS (Committee for Formulation of Agriculture Policy for Punjab State) (2013), "Agriculture Policy for Punjab", Report submitted to Government of Punjab, March 2013.

CGWB (Central Ground Water Board) (2016), State Profile, Government of India, Ministry of water resources, river development and Ganga rejuvenation, Faridabad, updated in March 2016, http://cgwb.gov.in/gw_profiles/st_AP.htm

CGWB (2015), "Groundwater Year Book of Haryana State (2014-2015)", Government of India, Ministry of water resources, river development and Ganga rejuvenation, Chandigarh.

CGWB (2014), "Dynamic Ground Water Resources of India, as on 31st March 2011", Government of India, Ministry of water resources, river development and Ganga rejuvenation, Faridabad.

CGWB (2013), "Master Plan for artificial recharge to groundwater in India", Government of India, Ministry of water resources, New Delhi.

CGWB (2006), "Dynamic Ground Water Resources of India, as on March 2004", Government of India, Ministry of water resources, Faridabad.

Chavas, D.R. et al. (2009), "Long-term climate change impacts on agricultural productivity in eastern China", *Agricultural and Forest Meteorology*, Vol. 149, pp. 1118–1128.

Chen J. Y. (2010), "Holistic assessment of groundwater resources and regional environmental problems in the North China Plain", *Environmental and Earth Science*, Vol. 61, pp.1037–1047.

Chen, S. et al. (2016), "Impacts of climate change on agriculture: Evidence from China", *Journal of Environmental Economics and Management*, Vol. 76, pp.105-124. http://dx.doi.org/10.1016/j.jeem.2015.01.005

China Water Risk (2016), Website, Last accessed February 2016. http://chinawaterrisk.org/

China Water Risk (2015), "2014 State of Environment Report Review", China Water Risk, Hong Kong. http://chinawaterrisk.org/resources/analysis-reviews/2014-state-of-environment-report-review/

Ciscar, J.C. et al. (2014), "Climate Impacts in Europe", The JRC PESETA II Project, Joint Research Centre (JRC) Scientific and Policy Reports, EUR 26586EN, European Commission, Seville, Spain.

Cook, B.I., et al. (2015), “Unprecedented 21st century drought risk in the American Southwest and Central Plains”, *Science Advance,* Vol. 1, e1400082.

Cooley, H. et al. (2016), “Water Risk Hotspots for Agriculture: The case of the Southwest United States”, OECD Food, Agriculture and Fisheries Paper N. 96, OECD Publishing, Paris.

Cosgrove, C. E., and W.J. Cosgrove (2011), “The Dynamics of Global Water Futures Driving Forces 2011 – 2050”, UNESCO, Paris, France.

CRED (Center for Research on the Epidemiology of Disasters) (2016), “EM-DAT Glossary”, EM-DAT, the international disasters database, Université Catholique de Louvain, Belgium http://www.emdat.be/Glossary (accessed 7 January 2016).

De Sherbinin, A. (2013), “Climate Change Hotspots Mapping : What Have We Learned ?” *Climatic Change*, Vol. 123/1, pp. 23-37.

Ding et al. (2007), “Detection, Causes and Projection of Climate Change over China: An Overview of Recent Progress”, *Advances in Atmospheric Sciences*, Vol. 24, No. 6, pp. 954–971.

Döll, P. (2009), “Vulnerability to the impact of climate change on renewable groundwater resources”, *Environmental Research Letters*, Vol.4/3. DOI:10.1088/1748-9326/4/3/035006

Döll, P. (2002), “Impact of climate change and variability on irrigation requirements: a global perspective”, *Climatic change*, Vol. 54, pp.269-293.

Döll, P. and Fiedler, K. (2008), “Global-scale modeling of groundwater recharge”, *Hydrology and Earth System Sciences*, Vol. 12, pp. 863–885.

Döll, P. et al. (2015), “Integrating risks of climate change into water management”, *Hydrological Sciences Journal*, Vol. 60/1, pp.4-13. DOI: 10.1080/02626667.2014.967250

Elliott, J. et al. (2014), “Constraints and potentials of future irrigation water availability on agricultural production under climate change”, *Proceedings of the National Academy of Sciences*, Vol. 111/9, pp. 3239–3244.

Famiglietti, J.S. et al. (2011). Satellites Measure Recent Rates of Groundwater Depletion in California’s Central Valley, *Geophysical Research Letters*, Vol. 38, p. L03403.

FAO (Food and Agriculture Organization) (2015a), CLIMPAG Website, available at: http://www.fao.org/nr/climpag/hotspots/index_en.asp

FAO and WWC (World Water Council) (2015), Towards a Water and Food Secure Future: Critical Perspectives for Policy-makers, White Paper, FAO and WWC, Rome, and Marseilles. http://www.worldwatercouncil.org/fileadmin/world_water_council/documents/publications/forum_documents/FAO_WWC_Water_and_Food_WhitePaper.pdf

Fischer, G. et al. (2007), “Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080”, *Technological Forecasting & Social Change*, Vol. 74, pp.1083–1107.

Foster S. and Garduño H. (2004), China: towards sustainable groundwater resource use for irrigated agriculture on the North China Plain, Case Profile Collect, World Bank, Washington, DC.

Fraser, E.D.G., et al. (2013), “Vulnerability hotspots: Integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought”, *Agricultural and Forest Meteorology*, Vol. 170, pp. 195-205.

Frenken, K. and V. Gillet (2012), “Irrigation water requirement and water withdrawal by country”, Aquastat., FAO, Rome Available from: http://www.fao.org/nr/water/aquastat/main/index.stm

Fuhrer, J., et al. (2013), “Water Demand in Swiss Agriculture – Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change”, ART-Schriftenreihe 19, Agroscope, Swiss Confederation, Bern. https://www.agroscope.admin.ch/agroscope/en/home/topics/plant-production/field-crops/kulturarten/cereales/publikationen-sortenlisten-sortenpruefung/_jcr_content/par/columncontrols/items/0/column/externalcontent.external.exturl.pdf/aHR0cHM6Ly9pcmEuYWdyb3Njb3BlLmNoL2VuLVVTL0VpbnplbH/B1Ymxpa2F0aW9uL0Rvd25sb2FkRXh0ZXJuP2VpbnplbHB1Ymxp/a2F0aW9uSWQ9MzMyMjc=.pdf

Fung, F. et al. (2011), “Water availability in +2◦C and +4◦C worlds”, *Philosophical Transactions of the Royal Society A*, Vol. 369, pp.99–116. doi:10.1098/rsta.2010.0293

Gandhi, V.P and Namboodiri, N.V. (2009), “Groundwater Irrigation in India: Gains, Costs and Risks”, Indian Institute of Management, Ahmedabad.

Garduño, H. et al. (2011), “India, Groundwater Governance case study”, Water Papers, World Bank, Washington DC.

Gassert, F. et al. (2013), Aqueduct Global Maps 2.0, The World Resources Institute, Washington DC.

Gerten, D. et al. (2011), “Global Water Availability and Requirements for Future Food Production”, *Water and Global Change (WATCH)*, October, pp. 885–899. doi:10.1175/2011JHM1328.1

Giordano, M. (2009), “Global groundwater? Issues and solutions” *Annual Review of Environment and Resources*, Vol. 34/1, pp.153–178. doi:10.1146/annurev.environ.030308.100251

Giordano, M. et al.(2004), “Water Management in the Yellow River Basin: Background, Current Critical Issues and Future Research Needs”, in IWMI Comprehensive assessment of water management in agriculture, International Water Management Institute, Colombo, Sri Lanka.

Giorgi, F. (2006), “Climate change hot-spots”, *Geophysical Research Letters*, Vol. 33, p. L08707, doi:10.1029/2006GL025734.

GIST Advisory (2013), “Trends and patterns of food production in Punjab: Bio-physical aspects”, GIST Advisory, Mumbai India.

Gleeson, T. et al. (2012), “Water balance of global aquifers revealed by groundwater footprint”, *Nature*, Vol. 488, pp. 197-200.

Gosain, A.K. et al. (2001), “Climate change impact assessment of water resources of India”, *Current Science*, Vol. 101/ 3, pp.356-371.

Haddeland, I. et al. (2014), “Global water resources affected by human interventions and climate change”, *Proceedings of the National Academy of Sciences*, 111/9,pp. 3521–3256. doi:10.1073/pnas.1222475110

Hanasaki, N. et al. (2008), “An integrated model for the assessment of global water resources – Part 2: Applications and assessments”, *Hydrology and Earth System Sciences*, Vol. 12, pp. 1027-1037.

Hare, W. L. et al. (2011), “Climate hotspots : key vulnerable regions, climate change and limits to warming”, *Regional Environmental Change*, Vol. 11, pp. S1–S13. doi:10.1007/s10113-010-0195-4

Hatton, T. et al. (2011), “The Australian State of the Environment 2011”, Report for the Australian Parliament, Canberra. https://www.environment.gov.au/science/soe/2011

Hejazi, M. I. et al. (2014), “Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies”, *Hydrology and Earth System Sciences*, Vol. 18, pp. 2859–2883. doi:10.5194/hess-18-2859-2014

Hijioka, Y. et al. (2014), "Asia" in *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327-1370.

Hill-Clarvis, M. et al. (2016), “Indian Insurance and Sustainable Development”, Report for the British High Commission in New Delhi and the Federation of Indian Chambers of Commerce and Industry, Earth Security Group. http://ficci.in/spdocument/20722/FICCI-ESG-INSURANCE-REPORT.pdf

Hirabayashi, Y., et al. (2013), “Global flood risk under climate change”, *Nature Climate Change*, Vol. 3, pp. 816–821. doi:10.1038/nclimate 1911

HLPE (2015), “Water for food security and nutrition”, a report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Huang, Q. et al. (2017), “Do water saving technologies save water? Empirical evidence from North China”, *Journal of Environmental Economics and Management*, Vol. 82, pp.1-16.

IEG (Independent Evaluation Group) (2011), “Adapting to Climate Change: Assessing World Bank Group Experience” Phase III of the World Bank Group and Climate Change, IEG, Washington DC.

IFPRI and Veolia (2015), “The murky future of global water quality”, White Paper, IFPRI and Veolia USA, Washington, DC.

Iglesias, A. and L. Garrote (2015), “Adaptation strategies for agricultural water management under climate change in Europe”, *Agricultural Water Management*, Vol. 155, pp. 113–124.

Ignaciuk, A. (2015), "Adapting Agriculture to Climate Change: A Role for Public Policies", OECD Food, Agriculture and Fisheries Papers, No. 85, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/5js08hwvfnr4-en

Ignaciuk, A. and D. Mason-D'Croz (2014), "Modelling Adaptation to Climate Change in Agriculture", OECD Food, Agriculture and Fisheries Papers, No. 70, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/5jxrclljnbxq-en

Ignaciuk, A. et al. (2015), “Better drip than flood: reaping the benefits of efficient irrigation”, *EuroChoices* Vol. 14/2, pp. 26-32.

Indian National Informatics Centre (2016a), “Irrigated area cropped once and more than once” (2011-2012), State Tables, in Input Survey Database, Agriculture Census Division, New Delhi. http://inputsurvey.dacnet.nic.in/statetables.aspx

Indian National Informatics Centre (2016b), ‘‘District-wise Distribution of Characteristics of Holdings by Size Class/Size Group” (2010-2011), State Tables, in Agricultural Census Database, Agriculture Census Division, New Delhi. http://agcensus.dacnet.nic.in/StateSizeClass.aspx

IPCC (Intergovernmental Panel on Climate Change) (2012), “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation”, in [Field, C.B. et al. (eds.), *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, UK, and New York, US, 582 pp.

IPCC (2008), “Analysing regional aspects of climate change and water resources” in Climate Change and Water, Technical Paper VI, IPCC Secretariat, Geneva.

Iyer, K. (2013), “The Grain Necessities”, in Jensen, D. et al. (eds), *Food: An Atlas*, map. https://www.scribd.com/document/202944804/Food-An-Atlas

Jiménez Cisneros, B.E., et al. (2014), “Freshwater resources”. In Field, C.B. et al. (eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability: Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, pp. 229-269.

Kendy, E. et al. (2003), “Policies drain the North China Plain: agricultural policy and groundwater depletion in Luangcheng County, 1949–2000”, Research Report 71, International Water Management. Institute (IWMI), Colombo, Sri Lanka.

Kiguchi, M., et al. (2015), “Re-evaluation of future water stress due to socio- economic and climate factors under a warming climate”, *Hydrological Sciences Journal*, Vol. 60/1, pp. 14-29.

Kim, C-G. (2013), “The Impact of Climate Change on the Agricultural Sector: Implications of the Agro-Industry for Low Carbon, Green Growth Strategy and Roadmap for the East Asian Region”, background policy paper for the East Asia Low Carbon Green Growth Roadmap project, Korea International Cooperation Agency.

Kleinen, T., and G. Petschel-Held (2007), “Integrated assessment of changes in flooding probabilities due to climate change”, *Climatic Change*, Vol. 82, pp.283-312.

Krar, P. (21 July 2016), “Three firms submit bids for validating energy consumed by agricultural pump sets in Punjab”, The Economic Times, India. http://economictimes.indiatimes.com/news/economy/agriculture/three-firms-submit-bids-for-validating-energy-consumed-by-agricultural-pump-sets-in-punjab/articleshow/53323392.cms

Krishan, G. et al. (2015), “Rainfall Trend Analysis of Punjab, India using Statistical Non-Parametric Test”, *Current World Environment* Vol. 10/3, pp.792-800.

Kumar, M.D. et al. (2011), “Inducing the shift from flat-rate or free agricultural power to metered supply: Implications for groundwater depletion and power sector viability in India”, *Journal of Hydrology*, Vol. 409, pp. 382–394.

Lapworth, D.J. et al. (2014), “Intensive Groundwater Exploitation in the Punjab – an Evaluation of Resource and Quality Trends”, British Geological Survey, Open Report OR/14/068.

Lau, W.K. and K-M. Kim (2012), “The 2010 Pakistan Flood and Russian Heat Wave: Teleconnection of Hydrometeorological Extremes”, *Journal of Hydrometeorology*, Vol. 13, pp. 392–403. http://dx.doi.org/10.1175/JHM-D-11-016.1

Liu, B., and R. Speed (2009), “Water Resources Management in the People's Republic of China”, *International Journal of Water Resources Development*, Vol.25, pp.193-208.

Liu, J. et al. (2014), “International trade buffers the impact of future irrigation shortfalls”, *Global Environmental Change*, Vol. 29, pp. 22–31. doi:10.1016/j.gloenvcha.2014.07.010

Liu, Y. et al. (2015), Agriculture intensifies soil moisture decline in Northern China, *Scientific Reports*, Vol. 5, Article number: 1126. DOI:10.1038/srep11261.

Luck, M. et al. (2015), “Aqueduct Water Stress Projections: Decadal projections of water supply and demand using CMIP5 GCMs”, The World Resources Institute, Washington DC.

Lui, B. (2006) "China’s Agricultural Water Policy Reforms", in OECD, *Water and Agriculture: sustainability, markets and policies*, OECD Publishing, Paris.

Luo, T., et al. (2015). Aqueduct Projected Water Stress Country Rankings, Washington D.C. http://www.wri.org/publication/aqueduct-projected-water-stress-country-rankings

MacDonald, A. M. et al. (2016), “Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations”, *Nature Geoscience*, Vol. 9, pp. 762-766.

Mahajan, G. et al. (2012), “Scope for enhancing and sustaining rice productivity in Punjab (Food bowl of India)”, *African Journal of Agricultural Research,* Vol. 7/42, pp. 5611-5620.

Mangat, H.S. (2016), “Water war between Punjab and Haryana”, *Economic and Political Weekly*, Vol. LI, N. 50.

Margat, J. and J. van der Gun (2013), Groundwater around the World: A Geographic Synopsis, CRC Press/Balkema, Taylor and Francis, London.

Maupin, M. et al. (2014),“Estimated Use of Water in the United States in 2010”, US Geological Survey Circular 1405, USGS, Washington DC.

Mekonnen, M. M. and A. Y. Hoekstra (2016), "Four billion people facing severe water scarcity", *Science Advances*, Vol. 2/2, e1500323, DOI: 10.1126/sciadv.1500323

Mendelsohn, R. et al. (2012), "The impact of climate change on global tropical cyclone damage", *Nature Climate Change,* Vol. 2/3, pp. 205–209. doi:10.1038/nclimate1357

Milly, P. C. D. et al. (2005), "Global pattern of trends in streamflow and water availability in a changing climate", *Nature*, Vol. 438, pp. 347–50. doi:10.1038/nature04312

Ministry of Statistics and Program Implementation (2016a), "Pattern Of Land Utilisation, All India And State wise" (2011-2012), Agriculture Chapter in Statistical Year Book, India 2015 (database), Government of India, New Delhi. http://mospi.nic.in/Mospi_New/upload/SYB2015/ch8.html

Ministry of Statistics and Program Implementation (2016b),"Net area under irrigation by source" (2011-2012), Irrigation Chapter in Statistical Year Book, India 2015 (database), Government of India, New Delhi. http://mospi.nic.in/Mospi_New/upload/SYB2015/ch12.html

Ministry of Statistics and Program Implementation (2016c), "Average Yield Of Principal Crops, All India And State wise." and "Production Of Principal Crops, All India And State wise." (2011-2012), Agriculture Chapter in Statistical Year Book, India 2015 (database), Government of India, New Delhi. http://mospi.nic.in/Mospi_New/upload/SYB2015/ch8.html

Mohinder, G. (2016), "Direct Delivery of Power Subsidy to Agriculture", Presentation at the South Asia Groundwater Forum, Jaipur, 1 June 2016.

Murgai, R. (2001), "The Green Revolution and the productivity paradox: evidence from the Indian Punjab", *Agricultural Economics,* Vol. 25, pp. 199–209.

Murray, S. J. et al. (2012), "Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model", *Journal of Hydrology*, Vol. 448-449, pp. 14–29. doi:10.1016/j.jhydrol.2012.02.044

NARCC (National Assessment Report on Climate Change)(2007), China's national assessment report on climate change, *Science Press*, Beijing.

National Bureau of Statistics of China (2016), Official statistic database, Beijing. (accessed January 2016).

National Commission on Population (2006), "Population projections for India and States 2001-2026", Office of the Registrar General & Census Commissioner, New Delhi, May 2006.

Nicholls, R.J. and A. Cazenave (2010), "Sea-Level Rise and Its Impact on Coastal Zones", *Science*, Vol. 328, pp. 1517–1521.

Nicholls, R.J. et al. (1999), "Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses", *Global Environmental Change*, Vol. 9, pp. S69-S87.

Nicholls, R.J., and R. S. J. Tol (2006), "Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century", *Philosophical Transactions of the Royal Society A*, Vol. 364/1841, DOI: 10.1098/rsta.2006.1754.

OECD (2016a), *Mitigating Droughts and Floods in Agriculture: Policy Lessons and Approaches*, OECD Studies on Water, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264246744-en

OECD (2016b), "OECD Council Recommendation on Water" [C(2016)174/FINAL], OECD, Paris. https://www.oecd.org/environment/resources/Council-Recommendation-on-water.pdf

OECD (2015a), *Drying wells, rising stakes: Towards sustainable agricultural groundwater use*, OECD Studies on Water, OECD Publishing, Paris. DOI: http://dx.doi/10.1787/978926423870-en

OECD (2015b), *Environment at a Glance 2015: OECD Indicators*, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264235199-en

OECD. (2015c), *The Economic Consequences of Climate Change*, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264235410-en

OECD (2014a), *Climate Change, Water and Agriculture: Towards Resilient Systems*, OECD Studies on Water, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264209138-en

OECD (2014b), "Global irrigation water demand projections to 2050: An analysis of convergences and divergences" [ENV/EPOC/WPBWE(2012)2/FINAL], OECD, Paris.

OECD (2013), *Water Security for Better Lives*, OECD Studies on Water, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264202405-en

OECD (2012), *Water Quality and Agriculture: Meeting the Policy Challenge*, OECD Studies on Water, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264168060-en

OECD (2010), *Sustainable Management of Water Resources in Agriculture*, OECD Studies on Water, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264083578-en

OECD (2009), *Managing Risk in Agriculture: A Holistic Approach*, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264075313-en

OECD/FAO (2015), OECD-FAO Agricultural Outlook 2015, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/agr_outlook-2015-en

Pandey, S. (2011), "Report on impact assessment of notification in Gurgaon town and adjoining industrial areas of Gurgaon district, Haryana", Central Ground Water Board, North Western Region, Chandigarh, December 2011.

Parish, E.S., et al. (2012), "Estimating future global per capita water availability based on changes in climate and population", *Computers & Geosciences,* Vol. 42, pp 79-86.

PSCST (Punjab State Council for Science and Technology) (2014), "Punjab State Action Plan on Climate Change", Department of Science Technology and Environment, Government of Punjab, February 2014.

Pfister, S. and P. Bayer (2013), "Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production", *Journal of Cleaner Production*, Vol. 30, pp. 1-11.

Phillips, S.P. et al. (2015), "Sustainable groundwater management in California" U.S. Geological Survey Fact Sheet 2015-3084 (ver. 2.2, February 2016), USGS, Washington DC. http://dx.doi.org/10.3133/fs20153084

Piao, S. et al. (2010), "The impacts of climate change on water resources and agriculture in China", *Nature*, Vol. 467, pp.43-51.

Piontek, F., et al. (2013), "Multisectoral climate impacts in a warming world", *Proceedings of the National Academy of Sciences*, Vol. 111/9, pp. 3233-3238. doi:10.1073/pnas.1222471110.

Planning Commission (2009), "Report of the Task Force on Irrigation", Government of India, New Delhi.

PRC (People's Republic of China) (2007), "China's National Assessment Report on Climate Change", Science Publishing House, Beijing.

Prein, A.F. et al. (2016), "Running dry: The U.S. Southwest's drift into a drier climate state", *Geophysical Research Letters,* Vol. 43, pp.1272-1279. DOI: 10.1002/2015GL066727.

Punjab Department of irrigation (2008), "State Water Policy - 2008", public draft, Government of Punjab, Chandigarh.

Punjab Department of Soil and Water Conservation (2016), "Status and scope for drip and micro irrigation in Punjab", Government of Punjab, Chandigarh. http://dswcpunjab.gov.in/contents/micro_irrigation.htm (accessed August 2016)

Punjab Department of Revenue, Rehabilitation and Disaster Management (2014), "Climate of Punjab", Government of Punjab, http://punjabrevenue.nic.in/for%20website/Climate%20of%20Punjab.htm (accessed August 2016).

Punjab Directorate of Agriculture (2016), "Introduction to Punjab", Government of Punjab, Chandigarh, http://agripb.gov.in/home.php?page=intpu (accessed August 2016).

Rang, A. et al. (2014), "Status paper on rice in Punjab", Rice Knowledge Management Portal, Punjab Government, Chandigarh, www.rkmp.co.in/sites/default/files/ris/rice-state-wise/Status%20Paper%20on%20Rice%20in%20Punjab.pdf (accessed August 2016).

Reager, J. T. et al. (2016), "A decade of sea level rise slowed by climate-driven hydrology", *Science*, Vol. 351/6274, pp. 699–704.

Ringler, C. et al. (2011), *Sustaining growth via water productivity: Outlook to 2030/2050*, IFPRI and Veolia, Washington DC.

Robinson, S., et al. (2015) "The international model for policy analysis of agricultural commodities and trade (IMPACT); Model description for version 3". IFPRI Discussion Paper No. 1483, International Food Policy Research Institute, Washington, DC, http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Rockström, J. and L. Karlberg (2009), "Zooming in on the global hotspots of rainfed agriculture in water-constrained environments", in S. P. Wani, et al. (eds.), *Rainfed agriculture: unlocking the potential*, CABI International.

Rockström, J. et al. (2010), "Managing water in rainfed agriculture—The need for a paradigm shift", *Agricultural Water Management,* Vol. 97/4, pp. 543–550, http://dx.doi.org/10.1016/j.agwat.2009.09.009.

Rockström, J. et al. (2009), "Future water availability for global food production: The potential of green water for increasing resilience to global change", *Water Resources Research*, Vol. 45, pp. 1–16. http://dx.doi.org/10.1029/2007WR006767.

Rodell, M. et al. (2009), "Satellite-based estimates of groundwater depletion in India", *Nature*, Vol. 460/7258, pp. 999-1002.

Rowley, R. J. et al. (2007), "Risk of Rising Sea Level to Population and Land Area", *Eos, Transactions American Geophysical Union* Vol. 88/9, pp. 105–107.

Sadoff, C. et al. (2015), "Securing Water, Sustaining Growth", Report of the GWP/OECD Task Force on Water Security and Sustainable Growth, Oxford University, Oxford, https://www.water.ox.ac.uk/wp-content/uploads/2015/04/SCHOOL-OF-GEOGRAPHY-SECURING-WATER-SUSTAINING-GROWTH-DOWNLOADABLE.pdf.

Sarkar, A. and A. Das, A. (2014), "Groundwater Irrigation-Electricity-Crop Diversification Nexus in Punjab: Trends, Turning Points, and Policy Initiatives", *Economic & Political Weekly*, vol xlix/ 52, pp. 64-73.

Schaldach, R. et al. (2012), "Current and future irrigation water requirements in pan-Europe: An integrated analysis of socio-economic and climate scenarios", *Global and Planetary Change*, Vol 94-95, pp. 33-45.

Scheffran, J. and A. Battaglini (2011), "Climate and conflicts: the security risks of global warming", *Regional Environmental Change,* Vol. 11(Suppl. 1), pp. S27-S39. http://dx.doi.org/10.1007/s10113-010-0175-8.

Schewe, J. et al. (2013), "Multimodel assessment of water scarcity under climate change", *Proceedings of the National Academy of Sciences*, Vol. 111/ 9, pp. 3245-3250, http://dx.doi.org/10.1073/pnas.1222460110.

Schlosser et al. (2014), “The future of global water stress: An integrated assessment”, Report N. 254, MIT Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA. http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt254.pdf

Shen, Y. et al. (2014), “Projection of future world water resources under SRES scenarios : an integrated assessment”, *Hydrological Sciences Journal*, Vol. 59/10, pp. 1775–1793.

Shen, Y. et al. (2010), “Projection of future world water resources under SRES scenarios: Water withdrawal”, *Hydrological Sciences Journal*, Vol. 53/1, 11–33, http://dx.doi.org/10.1623/hysj.53.1.11.

Shiao, T. et al. (2015), “India water tool”, Technical Note, World Resources Institute, February 2015.

Shrivastava, P. and Kumar, R. (2014), “Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation”, *Saudi Journal of Biological Sciences*, Vol. 22, pp. 123–131.

Siebert, S. et al. (2010), “Groundwater use for irrigation – A global inventory”, *Hydrology and Earth Sciences*, Vol. 14, pp. 1863-1880.

Singh, I. and K. Singh Bhangoo (2013), “Irrigation system in Indian Punjab”, MPRA Paper No. 50270, University of Munich, Munich, Germany.

Singh, J. (2013), “Depleting water resources of Indian Punjab agriculture and policy options - A lesson for high potential areas”, *Global Journal of Science Frontier Research*, Vol. 13/4.

Singh, R.B. (2001), “Impact of land-use change on groundwater in the Punjab-Haryana plains, India”, in *Impact of Human Activity on Groundwater Dynamics,* Proceedings of a symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, IAHS Publication No. 269.

Tan, D. (2014), “The state of China’s agriculture”, China Water Risk, Hong Kong, China, http://chinawaterrisk.org/resources/analysis-reviews/the-state-of-chinas-agriculture/.

Tao, F. et al. (2009), “Modelling the impacts of weather and climate variability on crop productivity over a large area: A new superensemble-based probabilistic projection”, *Agricultural and Forest Meteorology*, Vol. 149/8, pp.1266-1278.

Tao, F. et al. (2003), “Future climate change, the agricultural water cycle, and agricultural production in China”, *Agriculture, Ecosystems and Environment*, Vol. 95, pp. 203–215.

Taylor, R. G. et al. (2013), “Ground water and climate change”, *Nature Climate Change*, Vol. 3, pp.322-329.

Thom, et al. (2001), “Australia: State of the Environment 2001”, Independent Report to the Commonwealth Minister for the Environment and Heritage, CSIRO, Canberra, https://soe.environment.gov.au/sites/g/files/net806/f/soe2001.pdf?v=1487243878.

Thomson, A.M. et al. (2006), “Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China”, Agriculture, *Ecosystems and Environment*, Vol. 114, pp. 195–209.

UNDESA (United Nations Department of Economic and Social Affairs) (2015), “World population prospects: The 2015 revision”, United Nations, Department of Economic and Social Affairs, Population Division, New York, NY.

UNESCO (United Nations Education, Science and Cultural Organisation) (2010), “Climate change and adaptation for water resources in Yellow River Basin”, China, IHP VII Technical Document in Hydrology UNESCO Office in Beijing, 2010.

USBR (United States Bureau of Reclamation) (2014), “Climate impact assessment: Sacramento and San Joaquin Basins”, Prepared for Reclamation by CH2M Hill, USBR, Washington DC. www.usbr.gov/watersmart/wcra/docs/ssjbia/ssjbia.pdf

USBR (2012), "Colorado River Basin water supply and demand study", USBR, Washington DC. www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/CRBS_Study_Report_FINAL.pdf.

United States Census Bureau (2005), "Interim state population projections", USCB, Washington DC.

van Drecht, G. et al. (2009), "Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050", *Global Biochemical Cycles*, Vol. 23, pp. 1-19.

van Puijenbroek, P.J.T.M. et al., (2014), "Global implementation of two shared socioeconomic pathways for future sanitation and wastewater flows", *Water Science and Technology*, Vol. 71, No. 2, pp. 227-233.

Venkata, S. and J. Burke (2013), "Smallholders and sustainable wells", Food and Agriculture Organisation, Rome.

Villholth, K.G. et al. (2014), "Groundwater in global irrigated food production – The role of depleting aquifers", International Water Management Institute (IWMI), Colombo, Sri Lanka.

Vörösmarty, C. J. et al. (2000), "Global Water Resources: Vulnerability from climate change and population growth", *Science*, Vol. 289, p.284.

Vrba, J., and A. Lipponen (eds.) (2007), "Groundwater resources sustainability indicators", United Nations Educational, Scientific and Cultural Organization (UNESCO)- International Hydrogeological Program, UNESCO, Paris.

Wada, Y. et al. (2013), "Multimodel projections and uncertainties of irrigation water demand under climate change", *Geophysical Research Letters*, Vol. 40, pp. 4626–4632, http://dx.doi.org/10.1002/grl.50686.

Wada, Y. et al. (2012), "Nonsustainable groundwater sustaining irrigation: A global assessment", *Water Resources Research*, Vol. 48 (November), p.W00L06.

Wang, J. (2017), "Agricultural groundwater use in China: Challenges, solutions and outlook", Presentation given at the Global Forum for Food and Agriculture (GFFA), Berlin, January 2017. https://www.slideshare.net/ifpri/agriculture-and-groundwater-feeding-billions-from-the-ground-up

Wang, J. et al. (2014), "Overview of impacts of climate change and adaptation in China's agriculture", *Journal of Integrative Agriculture*, Vol. 13/1, pp. 1-17.

World Bank (2013a), "China 2030: Building a modern, harmonious, and creative society", World Bank and the Development Research Center of the State Council, People's Republic of China, Washington, DC

World Bank (2013b), "Turn down the heat - Climate extremes, regional impacts, and the case for resilience", International Bank for Reconstruction and Development, The World Bank, Washington DC.

World Bank (2001), "India Power Supply to Agriculture", Report No. 22171-IN, 15 June 2001, The World Bank, Washington DC.

WWF (Word Wildlife Fund) (2016), "Overall water risk, food producers (including Tobacco)", Map of the Water Filter, WWF and KFW–DEG, WWF Germany, Berlin.

Xie, J. et al. (2008), "Addressing China's water scarcity: Recommendations for selected water resource management issues", World Bank, Washington DC, http://documents.worldbank.org/curated/en/2009/01/10170878/addressing-chinas-water-scarcity-recommendations-selected-water-resource-management-issues.

Xiong, W. et al. (2010), "Climate change, water availability and future cereal production in China", *Agriculture, Ecosystems and Environment*, Vol. 135, pp. 58-69.

Young, A. (1989), *Agroforestry for Soil Conservation*, CABI, Wallingford, UK.

Yu, W. (2016), "Agricultural and Agri-Environment Policy and Sustainable Agricultural Development in China", Background Report for the OECD Secretariat, March 2016.

Zaveri, E. et al. (2016), “Invisible water, visible impact: groundwater use and Indian agriculture under climate change”, *Environmental Research Letters*, Vol. 11, Article 084005, http:dx.doi.org/10.1088/1748-9326/11/8/084005.

Zhang, L. et al. (2007), “Potential effects of climate change on runoff in the Yellow River Basin of China”, *Transactions of the American Society of Agricultural and Biological Engineers*, Vol. 50, pp. 911–918.

Zhang, C. and L. Diaz, L. (2014), “A multi-regional input – output analysis of domestic virtual water trade and provincial water footprint in China”, *Ecological Economics*, Vol. 100, pp.159–172, http://dx.doi.org/10.1016/j.ecolecon.2014.02.006.

Zhao, J., et al. (2008), “Opportunities and challenges of sustainable agricultural development in China”, *Philosophical Transactions of the Royal Society B*, Vol. 363, pp. 893–904.

2030 WRG (2030 Water Resources Group) (2012), “The Water Resources Group: Background, Impact and the Way Forward”, International Financial Centre, Word Bank Group, Washington DC.

2030 WRG (2009), “Charting our Water Future”, International Financial Centre, Word Bank Group, Washington DC.

Annex 2.A1

Methodological note on water risks hotspot determination and examples of OECD applications

2.A1.1 Defining and measuring water risks

There are multiple definitions of risks (e.g. OECD, 2009). Some associate it with uncertainty around an event, others separate the two notions. For instance, in the context of natural disasters, risks are the "expected losses of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period" (CRED, 2016). A more general definition would be the "exposure to uncertain unfavourable economic consequences" (OECD, 2009).[1] Here we will use the latter definition, which is slightly more specific than to say that a risk is a "consequence of an event or an activity with respect to something that human value" (OECD, 2013).

Assessing risk requires the identification of three factors (hazard, exposure, and in the context of climate change, vulnerability) that are rarely assessed in a systematic way. Hazard and exposure are key factors needed to estimate a risk. A hazard is "the potential occurrence of a natural or human-induced physical event that may cause" an impact (e.g. flood damages) (IPCC, 2012). The exposure is "the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected", e.g. the presence of a large population in a coastal area (Ibid.). When considering a population of heterogeneous individuals, vulnerability also plays a significant role. Vulnerability corresponds to "the propensity or predisposition to be adversely affected" (Ibid.), such as availability of sufficient stock of usable groundwater under drought. Vulnerability can be reduced by building a resilience to risks, e.g. by making investments that reduce the future vulnerability of a system (allocating land to annual crops instead of perennial crops under increasing water stress).[2] Multiple reports on water risks only focus on partial assessments, for instance by assuming—implicitly or not—that one factor is varying (often exposure) while the others are not (identical hazards, uniform vulnerability).

Water risks can be defined broadly as water-related challenges that threaten the ability of a user to secure water. In other words, such risks encompass any barrier to water security. OECD (2013) defines water security as the absence of four types of risks:

- Risk of insufficient water to meet demand in both the short and long-run, including drought;
- Risk of excess water, including flood;
- Risk of water of inadequate quality for a given use;
- Risk of disruption of freshwater systems, when pressure exceeds their coping capacity (resilience).

This definition will be used as reference thereafter, acknowledging that the project will focus primarily on the three first categories of risks that have been most studied in the literature and more directly linked to agriculture productivity (shortage, excess, and inadequate quality). Table 2.A1.1 presents a matrix of these risks and their three dimensions. Agriculture is subject to multiple water phenomena that it does not control, but it is also a major water using and a significant polluting activity (OECD, 2010 and 2012). Both exogenous and endogenous water risks have to be considered to fully understand the challenges for agriculture. Both types of risks can and often do impact agriculture.

Table 2.A1.1. Decomposing the main agriculture water risks

	Hazard	Exposure	Vulnerability
Water shortage	Insufficient water for plant development, especially for water intensive crops, Lack of pasture, unsuitability of area for livestock.	Depends on climate, natural endowment of surface and groundwater, competing demands, and type of crop or livestock.	Depends on the presence or absence of irrigation, access to wells, storage of water, water efficiency measures, institutional and policy mechanisms.
Water excess	Excess water preventing agriculture, soil erosion, surface and groundwater flooding, livestock health issues.	Depends on the geography of the location (elevation, slopes, distance from water ways), and on the type of crop.	Depends on the infrastructure limiting damages, institutional and policy mechanisms to cope with excess water.
Water quality deterioration	Unusable water systems, irreversible groundwater or soil contamination, health effects on livestock, plants and humans.	Depends on local hydrogeology, distance to the sources of pollution, timing of pollution, and type of agricultural activity and the toxicity, life span, concentration and volume of pollutants.	Depends on access to treatment, or alternative sources of usable water, institutional and policy mechanisms.

Source: Author's own work.

In a dynamic setting, another distinction can be made between changes in the average or in the variability of water related variables. In the former case, hazards may be increasing in impact, but remain consistent with respect to long-term trends in exposure. For instance, increasingly lengthy droughts or continuous water quality deteriorations are increasing risks that can be feasible to anticipate. For changes in the variability of water risks, hazards and/or exposure may increase in variability, creating much more challenging predictions (storms, etc.).

There are multiple means to quantify water risks operating at different scales or for different purposes (e.g. see OECD, 2013). Some of the key indicators, both general and agriculture-related are indicated in Table 2.A1.2. Some specific examples are outlined in Table 2.A1.3 (see also Jimenez-Cisneros et al, 2014: 249). At the watershed, national or international level, most of the effort has focused on assessing the risk of shortages. Groundwater is often differentiated—multiple indicators have been proposed (e.g. OECD, 2015a; Vrba and Lipponen, 2007) but are often less used. Water quality risks are more assessed locally and typically more difficult to evaluate at a broader level.

On the quantitative side, a number of water stress indicators rely on alternative versions of the withdrawal-to-availability ratio, defined as the annual water withdrawal divided by annual water availability at the basin scale, W/Q, where the W is annual freshwater off-stream withdrawal for agriculture, industrial and domestic sectors, and Q is annual renewable freshwater resources. Usually, the extent of water stress is categorised as no-stress ($W/Q < 0.1$), low stress ($0.1 < W/Q < 0.2$), moderate stress ($0.2 < W/Q < 0.4$), and high stress ($W/Q > 0.4$). This index has the advantage of reflecting the integrated effects of both the pressure from human society (the demand side) and hydrological system (the supply side) (Shen et al., 2014). An illustration is provided in Figure 2.A1.1, with water stress estimates (%) in OECD countries as of 2009.

Table 2.A1.2. Selected indicators of water risks found in international literature

Risk	Indicators	Time horizon	Definition	Example of studies
Quantity	Water stress index	Current and future	Annual water withdrawal divided by annual water availability at the basin scale.	Gassert et al. (2013)
	Water supply-demand gaps	Current	Difference between current demand and supply based on accounting methods	2030 WRG (2009)
	Crop water footprint	Current	Monthly water stress indices are multiplied by irrigation crop requirements	Pfister and Bayer (2013)
	Runoff and demand projections	Future	Projected runoffs from climate circulation models are compared with water demand projections (withdrawals and consumption)	Luck et al. (2015)
	Irrigation water requirements	Current and future	Assessing the current and future requirement using climate models and crop requirements	Döll (2002); Schaldach et al., (2012)
	Irrigation reliability	Current and future	Ratio of supply over demand for irrigation computed with crop and climate models	Ignaciuk et al. (2015)
	Non-renewable groundwater irrigation	Current	Combining crop water demand with surface water availability and groundwater recharge assessments	Wada et al. (2012)
	Groundwater development stress (GDS)	Current	Ratio of groundwater use over renewable recharge.	Margat and van der Gun (2013)
	Groundwater footprint	Current	A measure of GDS is multiplied by the area of use and then divided by the aquifer area.	Gleeson et al. (2012)
	Groundwater dependent crops	Current and future	Accounting for crops irrigated by groundwater over depleting aquifers	Villholth et al. (2014)
	Distribution of water-stressed basins	Current and future	Distributions of basins with various extents of water stress as defined by: (a) withdrawal to availability ratio (W/Q) and per capita water availability (Q/c).	Shen et al. (2014)
	People in water stressed areas	Current	Assessing cultivated rainfed land with climate and aridity indices	Rockström et al. (2010)
	Flood damages	Current	Estimation of economic damages	EM-Dat (CRED, 2016)
Variability	Irrigation reliability	Future	Climate projections on agriculture are mixed with scenarios on irrigation using a global multi-market partial equilibrium model	Ignaciuk and Mason D'Croz (2014)
	Water security for agriculture	Future	Full water security modelled as a counterfactual with a global multi-market partial equilibrium model of agriculture	Sadoff et al. (2015)
	Drought frequency	Current and future	Consecutive dry days per year	IPCC (2012)
	Flood propensity	Current and future	Period to a major precipitation event (compared to those in a reference period)	IPCC (2012)
	Population at risk of floods	Future	Population potentially affected by the change in probability of a 50 year (or lower) flooding event under climate change	Kleinen and Petschel-Held (2007)
Quality	Emissions simulation	Future	Loadings are modelled based on past data and simulated emissions are projected using a partial equilibrium model of agriculture	IFPRI and Veolia (2015)
	Salinity risks	Current and future	Projections of constraints via satellite based land and surface and ground measurements	Bennett (1998)

Source: Authors' own work based on the reviewed literature.

Table 2.A1.3. Examples of methodologies used to assess water risks

Water quantity risk indicator	Study	Models used to calculate water demand and supply	Models used to calculate agriculture requirement	Future scenarios considered
Water supply, water demand, water stress, seasonal variability	Luck et al. (2015)	6 CMIP5 GCMs and projections of socioeconomic variables were derived from the Shared Socioeconomic Pathways (SSPs) hosted at IIASA	Irrigated area and irrigation efficiency using country-level regressions	Two climate scenarios (RCP4.5 and RCP8.5) and two shared socioeconomic pathways (SSP2 and SSP3)
Water Stress Index	Ringler et al. (2011)	International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT).		Four Economic Growth scenarios: (BAU), Low-Carbon, Grey, and Blue World
Short term (2020-2030) and long term (2071-2100) climate impacts	Ciscar et al. (2014)	Long term: 2080'S DSSAT, the models simulate daily phonological development and growth in response to environmental factors (such as climate including the effect of C02) and management (considering crop variety, N fertilisation, irrigation). The main output is "agricultural yield change". Short term: Compared to the baseline for the year 2000 on the CropSyst crop model.	BioMA-cropSyst, to assess crop yields (t/ha)	ENSEMBLES E1 scenario and Reference (BAU) simulation models
Water Stress Indicators	Vörösmarty, et al. (2000)	Water balance model (WBM) to calculate runoff	Irrigated land area and national use statistics	Climate Change data: Canadian Climate Center general circulation model (CGCM1) and the Hadley center circulation model HadCM2
The expected gap between 2030 demand figure and currently planned supply	2030 WRG (2009)	Water 2030 global water supply and demand model	Ag. Production based on IFRI IMPACT-water base case	Country specific base case scenarios for India, China, South Africa and Sao Paulo
Water management in rainfed agriculture	Röckstrom et al. (2010)	Link between climate and poverty is investigated. Thereafter, the number of people living in water-constrained agricultural areas is estimated. Based on this analysis, the global hotspots for rainfed agricultural areas in water-constrained environments are identified. Data on land use were derived from the Global Land Cover data set (GLC2000, 2003), in which the class 'cultivated and managed areas' was chosen to represent the total agricultural area. Second, a data set produced by the FAO (Food and Agriculture Organization, the United Nations) was used to represent irrigated agricultural land use. Water constraints were defined in terms of hydroclimate and described by an aridity index (AI)4 provided by the FAO (2006) using climatic variables in the data set CRU CL 2.0		n/a

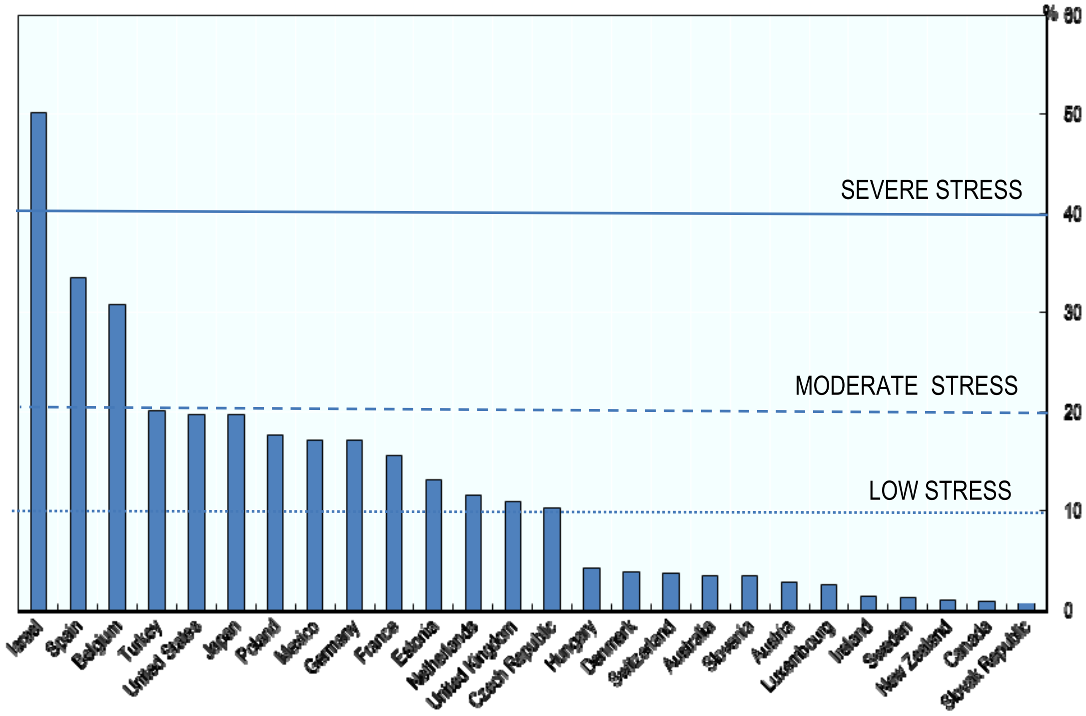
Table 2.A1.3. Examples of methodologies used to assess water risks (*cont.*)

Water quantity risk indicator	Study	Models used to calculate water demand and supply	Models used to calculate agriculture requirement	Future scenarios considered
Water quality indicators, BOD, N, and P levels	IFPRI and Veolia, (2015)	Using a variety of compiled data sets on population, agriculture, economic growth, climate, municipal wastewater treatment facilities and a newly developed global quality loading model (IGWQLM, IFPRI Global Water Quality Loading Model), the study examines the status of three key water quality parameters – biochemical oxygen demand (BOD), nitrogen, and phosphorus – by estimating their loadings into the water environment in a base period (2000-2005) and in 2050 under six alternative future scenarios focusing on domestic pollution as well as agriculture pollution from livestock and eight key staple crops.		Australia's Natural Science Agency, Commonwealth Scientific and Industrial Research Organisation (CSIRO): medium, optimistic, and pessimistic); MIROC (medium, optimistic, and pessimistic).
Water-related risks on a global scale, focusing upon four headline risks: (1) droughts and water scarcity; (2) floods; (3) inadequate water supply and sanitation; and (4) ecosystem degradation and pollution	Sadoff et al. (2015)	Consequences of hydrological variability for food production were modelled with the IMPACT model, a partial equilibrium agriculture sector model linked with a global hydrology model, a global water supply and demand model, and a gridded global crop simulation model. The model was calibrated to reproduce production averaged over the years 2004-2006.		
Impact of climate change and variability on irrigation Requirements: A Global Perspective	Döll (2002)	The study uses a global irrigation model, with a spatial resolution of 0.5◦ by 0.5◦, to analyse the impact of climate change and climate variability on irrigation water requirements. The study computes how long-term average irrigation requirements might change under the climatic conditions of the 2020s and the 2070s, as provided by two climate models, and relates these changes to the variations in irrigation requirements caused by long-term and inter-annual climate variability in the 20th century.		ECHAM4 climate change scenarios; HadCM3 climate change scenario;

Source: Authors' own work based on the reviewed literature.

Figure 2.A1.1. Water stresses in OECD countries

2013 or latest year available; water abstraction as a % of renewable resource



1. Water stress: below 10% = no stress; 10-20% = low stress; 20-40% = medium stress; above 40%: severe stress.
Source: OECD (2015b).

Estimating scarcity water risks for agriculture requires calculating current or future water withdrawal for agriculture. This encompasses assessing current irrigated crops water use and future crop water requirements. Crop calendars, area equipped for irrigation, and water quality also play an important role in the water risk calculation. Box 2.A1.1 summarises the basic steps to estimate water supply and demand.

Box 2.A1.1. Estimating current and future water consumption in agriculture

Water demand calculations rely on estimates of water withdrawal or water consumption. Water withdrawals refer to the volume of freshwater abstraction from surface or groundwater and water consumption to the water withdrawn and not returned to the environment (evaporated or incorporated into a product). Calculations of water quantity take into account water used for agronomic needs and possible changes in water efficiency or water losses in irrigation. It is important to include groundwater abstraction when calculating water quantity risk because groundwater accounts for over 40%of the total consumptive irrigation water use.

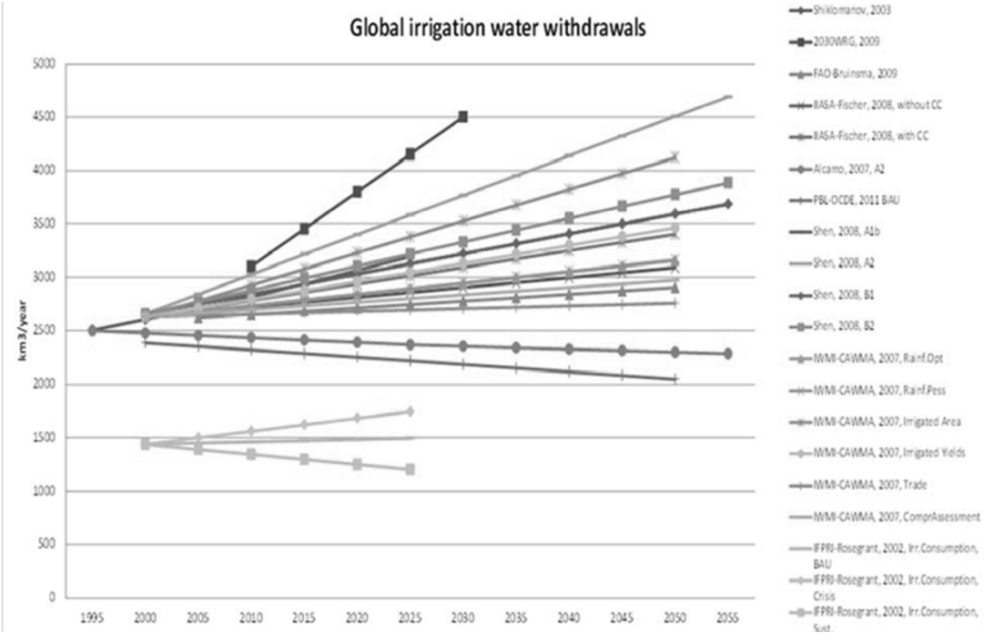
Agriculture crop water use is calculated using irrigated crop calendars, actually irrigated crop area, area equipped for irrigation, crop yield data, and irrigation crop consumption of a specific number of crops, or crop group. Irrigated crop calendars provide details on monthly occupation rates of the area equipped for full control irrigation actually irrigated for each crop. These calendars are created for a specific year for which the data is available. Irrigated water demand can be calculated for both surface water and groundwater. For the most part, when calculating water demand from irrigation, the total area equipped for irrigation is used but this can lead to demand overestimation.

To calculate future water risks to agriculture, assumptions on key parameters are made by analysing past statistical relationships. Calculating future water demands for a given area requires taking into account future climate scenarios and estimates on the most likely type of crops grown. Calculating the future demand for irrigation requires assumptions to determine the crops water use efficiency trends. These computations may also need to account for water supply available for agriculture, which depends on competing demands, infrastructure investments and climate change.

Projecting the effects of climate change on future irrigation water demand is a challenging task. Increased temperatures augment evapotranspiration but also accelerate plant growth (increasing the speed of accumulation of “growing degree days”, a heat index used to measure the time of plants to reach maturity). Furthermore, higher crop yields are obtained with high evapotranspiration but slower plant development, particularly during the growth period. So increased water demand may also lead to lower yields. The choice of modellers to focus on growing degree days or fixed duration and to look at crop yields for certain water or variable water demand for certain production will lead to diverse responses.

Uncertainties associated with these variables and considerations can result in wide differences in projections. Figure 2.A1.2 shows the projections of 19 simulation exercises on irrigation demand in the future.

Figure 2.A1.2. Irrigations projections from 19 simulations



Source: Frenken and Gillet (2012), OECD (2014b).

Multiple indices are used to measure the frequency and severity of extreme water events (OECD, 2016a). Droughts are measured by looking at soil moisture, consecutive dry days or the Palmer index. Flood risks are characterised by the period between two major precipitation events, the total precipitation, and damage costs.

Regarding water quality risks, identifying agriculture production exposed to contaminated water or areas vulnerable to agriculture water pollution is challenging. Globally, the methods used to monitor water quality are poorly developed, especially for pesticides (OECD, 2012). Additionally, differing drinking and environmental water standards between countries hinders global comparative assessment of water quality risks. Groundwater pollution is even harder to document mainly because of the costs involved in groundwater sampling.

2.A1.2. Defining future water risk hotspots for agriculture

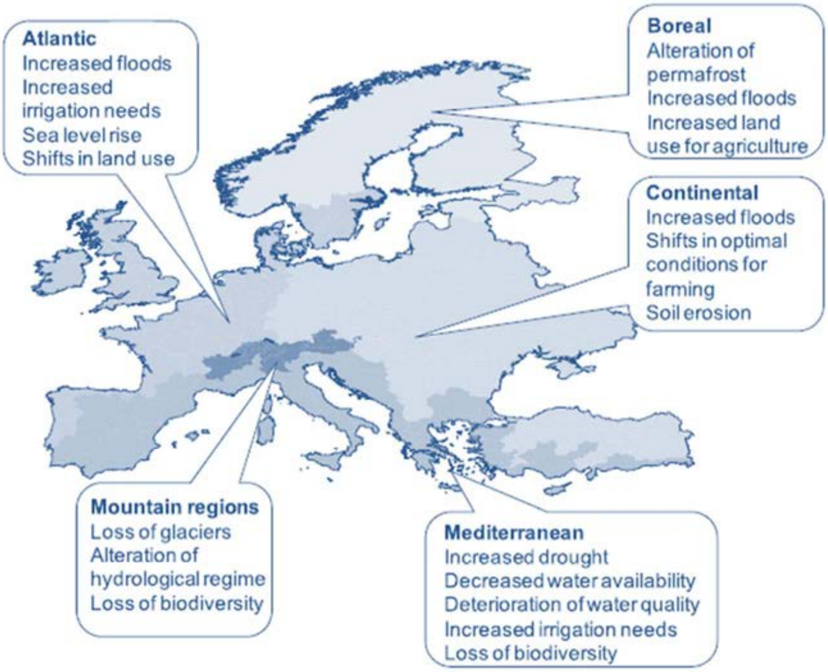
Defining future water risk hotspots for agriculture requires the measurement of water risks affecting agriculture, and plausible ways to project these risks in the future. Ideally this could be done by superposing current and future assessments of water risks with expected production areas and activities. Integrated models can help move in this direction (e.g. Schlosser et al., 2014). But the presence of multiple types of water risks, various agriculture activities, and alternative expected futures for both agriculture and water risks may complicate the exercise or increase the uncertainty of outcomes, especially at larger scales.

As a first step, separating the problems into three dimensions may help set up plausible hypotheses that can then be tested with models.[3] Three questions can guide this effort:

- What is the time horizon of the exercise? Current modelling exercises tend to focus either on a medium run (ten years- 2024-2030) or longer term (2050 and/or 2070) when considering climate change effects.
- What is the agriculture outlook looking like in the future under current conditions? The goal is to set a counterfactual of agriculture with reasonable expectations on supply and demand at the decided time horizon. It is important to know production levels by major activities and where these commodities will be produced and distributed. Historic trends can be used to gauge parameters in the future, even if they are generally not sufficient (unless on a short-term horizon) for projections.
- What types of water risks are expected to be observed and where could they coincide with highly productive agriculture areas? Characterising the main water risks may be done qualitatively using past events, trends, climate projections and expert solicitation. On this basis, selected indicators can be used to measure past, current and projected future water risks (see, e.g., section 2.A1.1). Ideally this requires information on potential hazards, exposure and vulnerability. Interactions with agriculture may be multiple, concerning water supply and demand factors, but also the evolution of agriculture management practices.

Figure 2.A1.3 illustrates some of the information necessary to move forward, with an identification of critical future agriculture water risks due to climate change in Europe. It was generated by reviewing the findings of multiple studies on different types of water risks using climate models. Agriculture will face dramatically different risks across the continent. Some regions will face a greater set of risks than others. In particular, the Mediterranean region could be seen as a regional hotspot in view of its multiple challenges: it will face increased droughts, declining water availability, increased irrigation requirements (higher crop water requirements), and declines in water quality and biodiversity impacts. A secondary hotspot may be found in some coastal areas of the Atlantic region that could face sea level rise, flood risks, as well as increased irrigation requirements. To identify hotspots for agriculture production, such assessment would then need to be combined with an evaluation of future agriculture production hotspots in Europe.

Figure 2.A1.3. Regional agriculture water risk assessment under climate change



Source: Iglesias and Garrote (2015).

The second step requires setting appropriate thresholds to define the hotspots. Depending on the degree of detail taken in the first-step assessment several options can be considered.

- *Where the future water risks and agriculture projections are well known*, the thresholds can be decided based on the distribution of the risks on agriculture (or the estimation thereof). The threshold cut-off may be defined statistically: above a certain level of risk (or hazard or exposure or vulnerability of agriculture production) that is deemed critical; or relatively by including regions that account for a higher quintile of risks or agriculture production compared to others.
- *Under partial or incomplete information on future water risks hotspots for agriculture*, for instance with an assessment combining multiple studies and datasets that do not all fully agree or that are insufficient to help estimate production levels and risks: the goal will be to look for regions with a consistently higher level of projected agriculture water risks (combined water risks and agriculture importance) compared to others, based on available evidence. The absence of contradiction around the hotspots will also help. Thresholds may be substituted by a selection of few regions in the absence of quantifiable risk estimates. The approach should seek validation, potentially via a consultation with experts from different fields, to avoid costly errors.
- *Where critical information on water risks or agriculture is unavailable*, *or where information only focuses on a limited area*, a hotspot approach may not be recommended, as it will run the risk of missing hotspots. A general prioritisation exercise may be used instead, considering the entire area (region, country), and allocating investments partially to those areas deemed to be more subject to risk.

Threshold levels are proposed for illustrative purposes (see Table 2.A1.4).

Table 2.A1.4. Examples of possible thresholds to define future water risk hotspots for agriculture

	Based on a comprehensive assessment (via a self-modelling exercise)	Based on partial assessment (using secondary data)
Water shortage	High category (e.g. W/Q>4)or higher quintile of water stress index and/or higher probability of droughts geospatially defined.	Areas consistently found to be at higher risks (high water indices, higher pollution, or higher probability of extreme events) among modelling studies (present and future).
Water excess	Higher probability of floods (e.g. < 1 in 100 years) geospatially defined.	
Water quality issue	Selection based on geospatially defined surface and groundwater quality projections: leading areas in terms of projected deterioration or lowest quality indices.	
Agriculture targets	Hotspot areas selected based on a superposition of the spatial allocation of future water risk with that of expected water-dependent intensive or productive agriculture activities	Predefined risk areas consistently seen as top 1-5 in terms of production or value of selected agriculture products.

Source: Authors' own work.

This menu of options may not be relevant in the presence of a heterogeneous level of information across locations. If a regional assessment of hotspots relies on good information from one part of the region, and lacks information from another, efforts should be taken to ensure that such information heterogeneity does not affect the hotspot determination. For instance, this may encompass a preliminary comparison of available variables everywhere, or increasing data collection and analysis where information is not as immediately available, or allocating a certain level of risks to all areas without sufficient information. If differences are too large across regions, the hotspot approach may not be worth pursuing.

These steps could be applied to any specific scale, since the hotspot approach focuses on relative risks. However, applying the method at a broader or narrower scale may matter in terms of the magnitude of the impacts. Hotspot regions in water abundant countries are less vulnerable to negative impacts on agriculture than in less water-endowed semi-arid countries. The following subsection will discuss multiple examples of partial or more advanced applications at different scales.

2.A1.3. The use of the hotspot approach in OECD countries

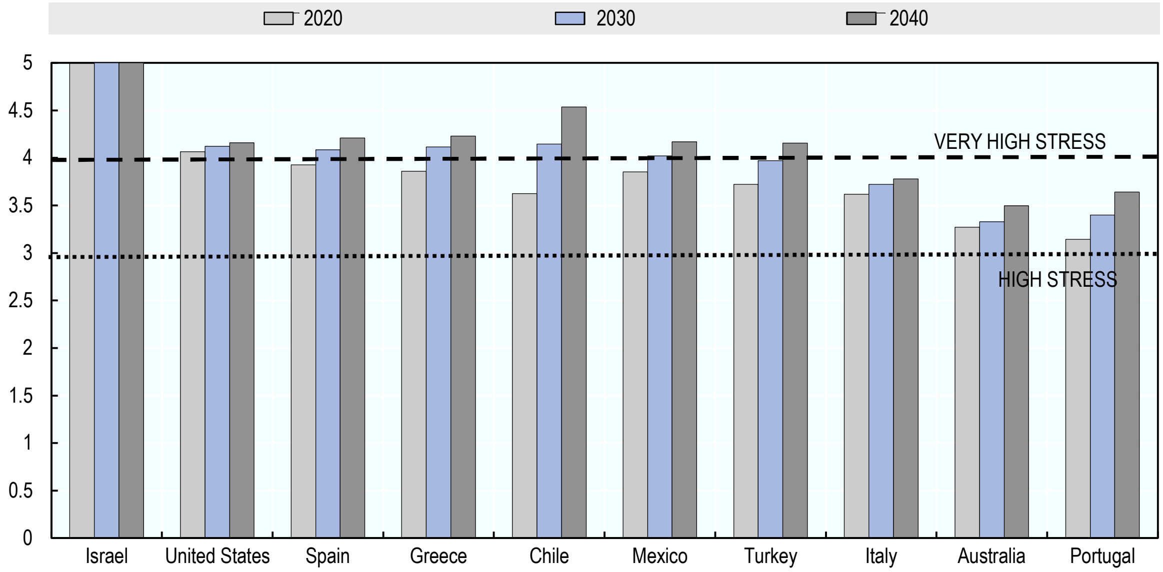
Examples from the literature illustrate the range of methods and scales of application of the hotspot approach to determine current or future water risks for agriculture. The emphasis is on diversity; some examples determine actual points on maps while others focus on larger regions and some multiple risks, and others focus on a specific risk. Most of these studies do not fully assess future water risk hotspots for agriculture, but do capture several dimensions of the problem in their varied assessments.

At the international level, recent efforts have focused on using variants of the water stress index to determine water risks. The World Resource Institute's Aqueduct project has applied multiple indicators to spatially define water risks. In particular, Luo et al. (2015) published a 165 country ranking of water stress for 2020, 2030, and 2040, using projections of water stress indices (based on supply and demand projections). Interestingly, they decompose these risks into their contribution to three sectors: domestic, industrial and agriculture sector.

Figure 2.A1.4 shows the results of their agriculture sector estimations for OECD countries rated at high or very high stress as of 2020 (with a water stress index over 3 or 4). According to this metric, only two OECD countries' agriculture sectors would face high water stresses in 2020 (Israel and the United States), but five other countries would join them in this category by 2040 (Spain, Greece, Chile, Mexico and Turkey). As shown in Figure 2.A1.5, agriculture also accounts for the highest component of the overall water risk of OECD average figures. Furthermore, Luo et al. (2015) results (Figures 2.A1.6 and 2.A1.7) suggest that on average OECD countries' agriculture sectors would be less at risk of water shortages under what they define as "pessimistic" climate scenario (high GHG emissions projections) than under an "optimistic" scenario (low

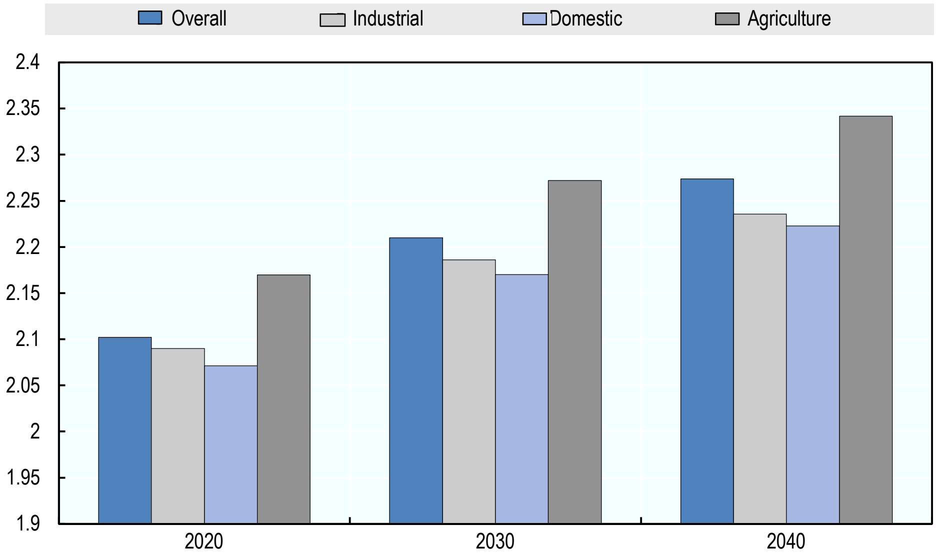
GHG emission projections) Precipitation could increase in many OECD countries in such pessimistic scenario (see, e.g. Ignaciuk and Mason D'Croz, 2014).[4]

Figure 2. A1.4. Estimated water stress indices in the agriculture sector, leading OECD countries, 2020-40



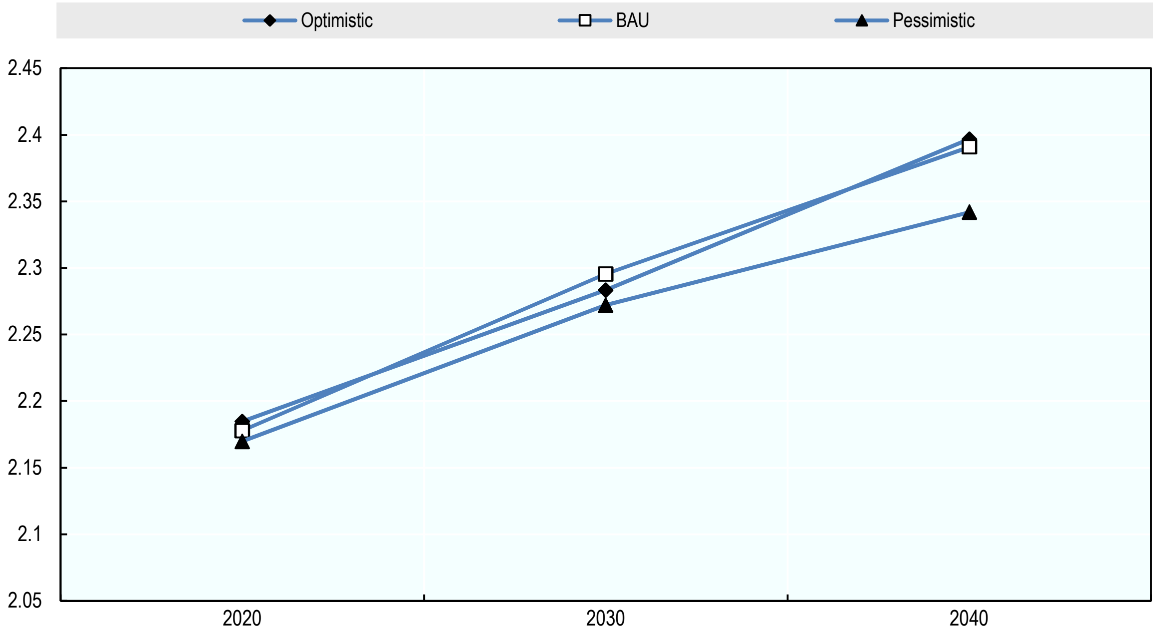
Source: Derived from Luo et al. (2015).

Figure 2.A1.5. Average water stress index for OECD countries under the Luo et al. (2015) pessimistic scenario



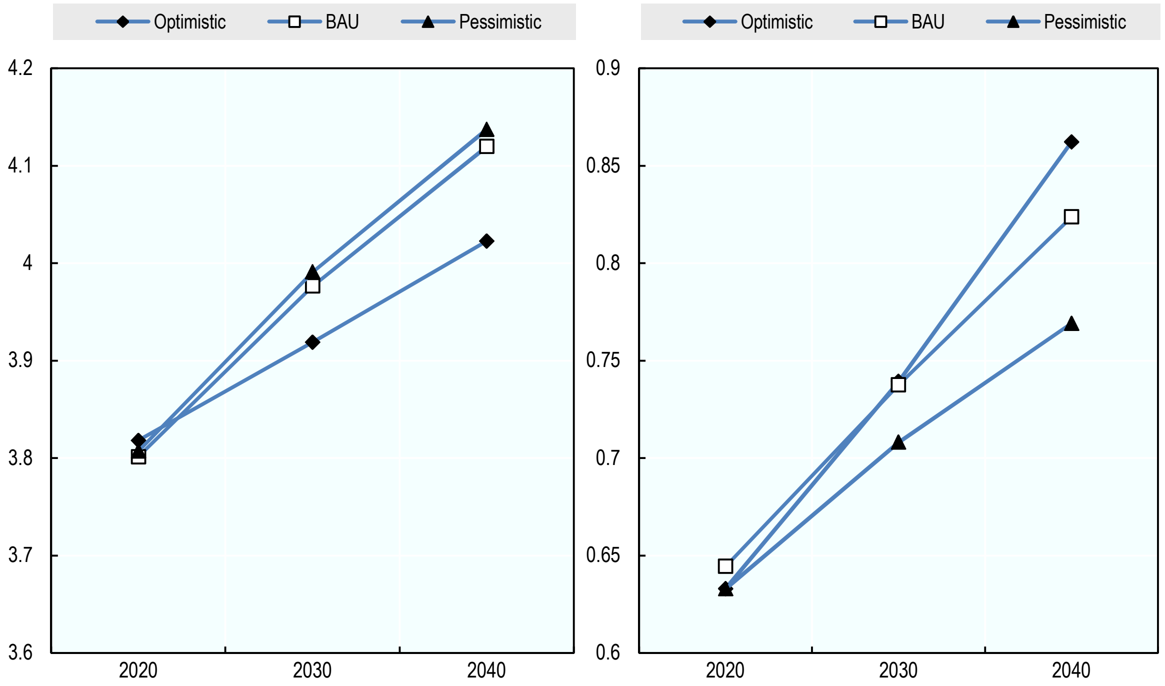
Source: Derived from Luo et al. (2015).

Figure 2.A1.6. Average water stress index for agriculture in OECD countries under Luo et al. (2015) scenarios



Source: Derived from Luo et al. (2015).

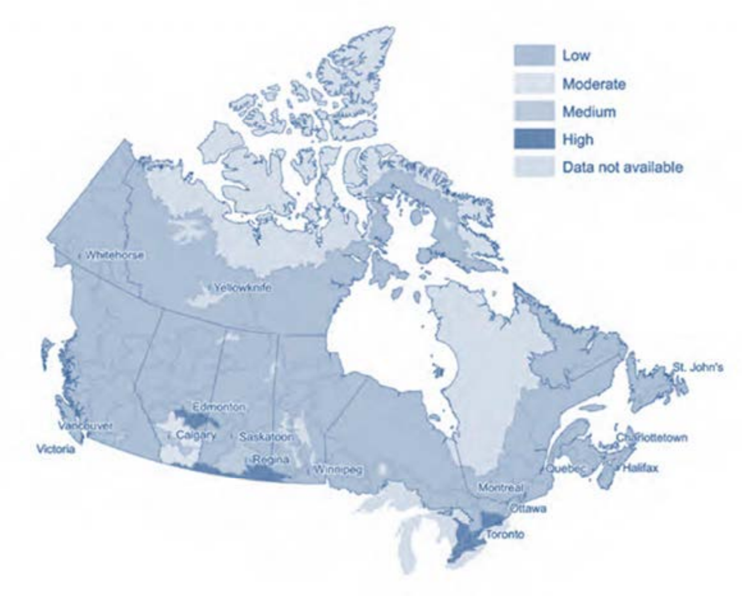
Figure 2.A1.7. Future water stress for agriculture for the top 10 (left) and bottom 10 (right) OECD countries under three scenarios



Source: Derived from Luo et al. (2015).

At the national level, multiple countries have conducted water stress assessments, but fewer explicitly consider agriculture. Figure 2.A1.8 shows the example of Canada's water stress. Despite its abundant water availability at the national level, there are limits to this abundance: "Canada does not have unlimited blue or green water available for agriculture expansion or intensification" (CCA, 2013). Furthermore as shown in Figure 2.A1.8, Canada already faces significant risks in some regions; there are "high threats to water availability in parts of interior British Columbia, the Prairie provinces, and southern Ontario, with significant water-based limitation to current agriculture productivity in some regions" (CCA, 2013). If the study does not consider the future risk hotspots explicitly, it does indicate areas that may continue to be at stress. This example confirms the importance of defining hotspots at an appropriate scale. A research at a large scale could mask more problematic areas- even if the problem there can be highly critical.

Figure 2.A1.8. Water stress in Canada (as of 2013)

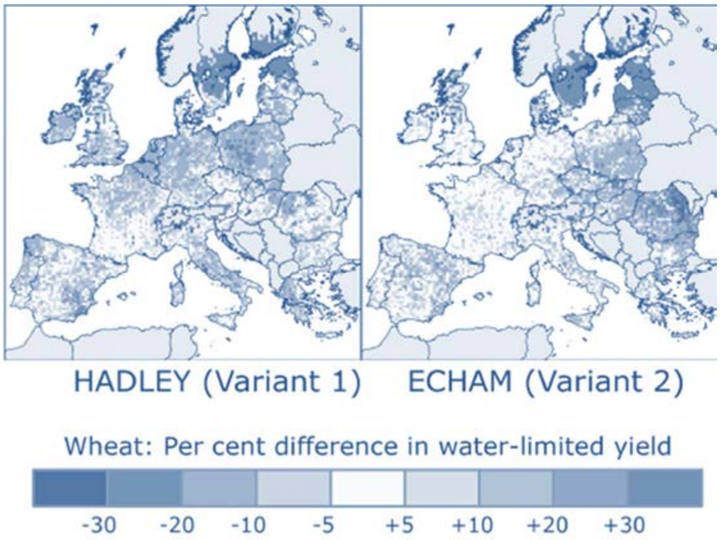


Source: CCA (2013).

Focusing on climate change risks at the crop level, Figure 2.A1.9 shows the expected water-limited yield difference for wheat in Europe in 2030 (Ciscar et al., 2014). The assessment combines emission scenarios, several global climatic circulation models (Hadley and ECHAM) and crop models to estimate yield effects. There are broad similarities across the two models, such as the observed higher yields in the North and reduced yields in Central Europe, but also significant differences notably in the South.

Cook et al. (2015) analysed the future severity of droughts in the continental United States, using a two-step process to determine water risk hotspots (Figure 2.A1.10). The study is based on multiple simulations and uses three drought risk indices: the Palmer drought index and the superficial and deeper soil moisture indices projected to the period 2050-99. The exercise was conducted for a specific IPCC scenario of emission (RCP 8.5), but integrates results from multiple modelling studies. The authors then looked at the variability of drought impacts between the three drought indices and the two regions. Results show a higher prevalence of drought in the Central Plains and Southwest regions, which are also large agriculture regions (upper part of Figure 2.A1.10) and in particular the Southwest region will face more intensive "mega-drought" episodes (lower part of Figure 2.A1.10).

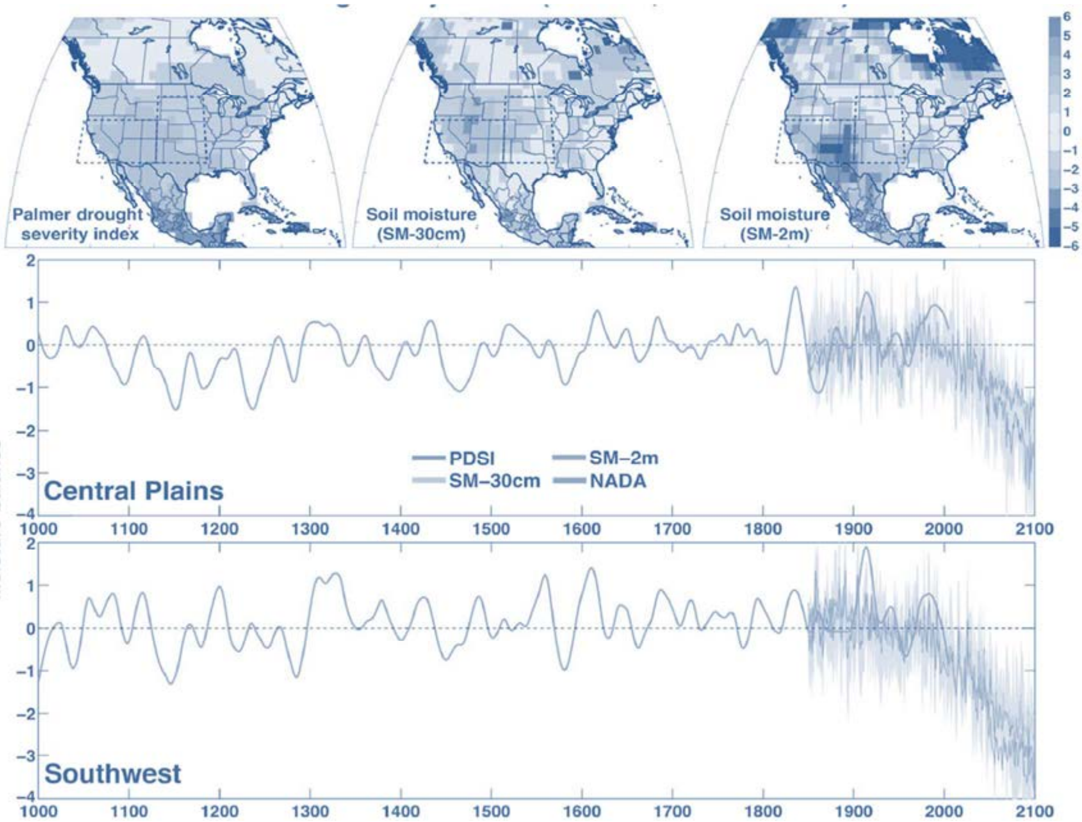
Figure 2.A1.9. Water-dependent yield effects of climate change on wheat in Europe in 2030



Source: Ciscar et al. (2014).

Figure 2.A1.10. Projected drought indicators in North America, 2050-99

Top panel: Drought maps using the three indicators (Palmer drought severity index, superficial and lower soil moisture) for North America; Middle and lower panel: evolution of these indicators for the Central Plains and Southwest regions of the United States



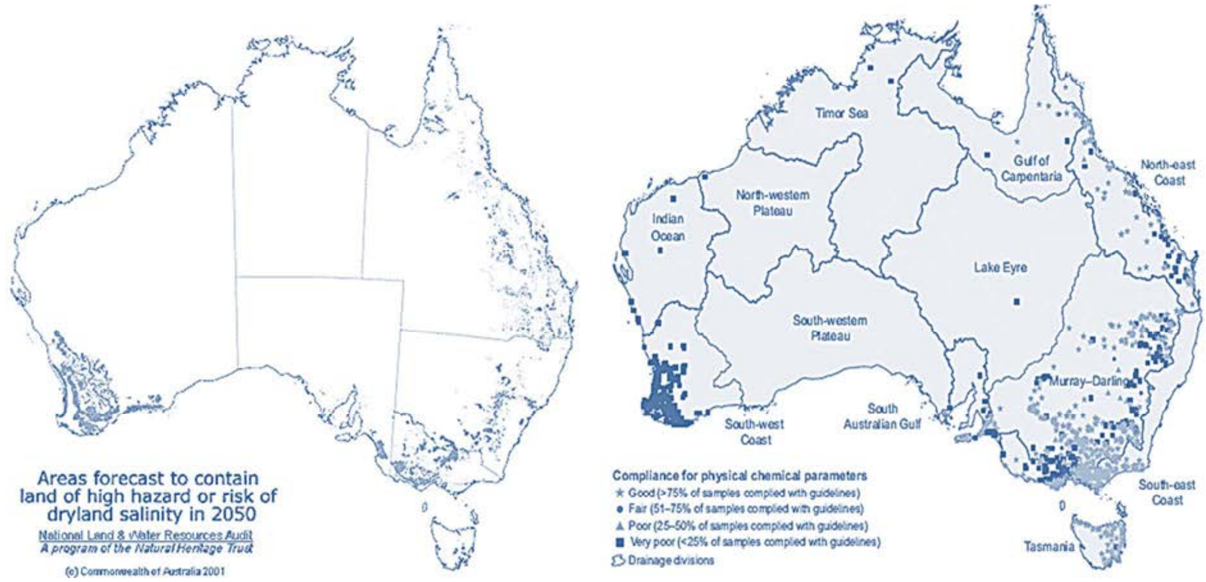
Source: Cook et al. (2015).

In the Flanders region of Belgium, the Government of Flanders has launched programmes to identify areas at risk of floods and droughts. It identifies local hotspots (“signaalgebieden”) for flooding, or areas where the geography does not match with the expected areas sensitive to water overflow. The Government of Flanders is also developing a model for droughts, based on a series of indicators, to be supported by a soil moisture monitoring network. Existing data is available, but there is a low awareness and use of data; more generally the risk of droughts should be more widely explained.

Critical water quality issues are also subject to risk mapping and hotspot identification exercises. As part of an assessment of land and water resources, Australia conducted a geospatial assessment of expected areas with high hazards or dryland salinity risk (Figure 2.A1.11 left panel, Thom et al., 2001). Such salinity results from the mismanagement of water resources often due to land clearance or the presence of shallow rooted plants. These plants let the water drain to aquifers, raising water table, thereby elevating salts to the surface where the water then evaporates. The projection accounted for land use change and climate change. A more recent salinity assessment (Figure 2.A1.11 right panel) shows that the areas found to be at risk in 2011 are consistent with this earlier map (Hatton et al., 2011).

Figure 2.A1.11. Risks of dryland salinity in Australia

Left panel: projected salinity risk hotspots, Right Panel: audit of compliance as of 2011

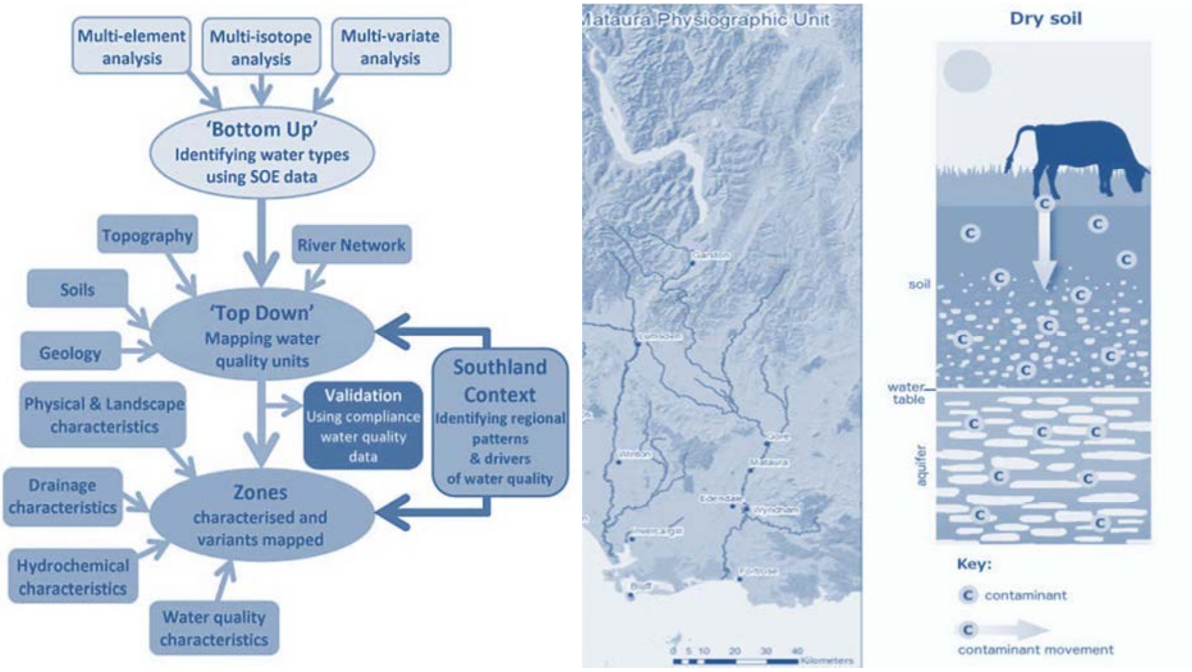


Source: Thom et al. (2001) and Hatton et al, (2011).

The Southland region in New Zealand has used advanced targeting methods to manage water quality damages primarily from agriculture at the regional and local levels. In particular, the Southland region has developed an approach that can help decide which area is the most at risk of water quality impacts (the Mautaura area is shown on the central panel of Figure 2.A1.12), support the characterisation of risks (nitrate infiltration to groundwater, right panel) and customise responses to get the highest results. If this method is used primarily to manage current water risk from agriculture, which may also affect agriculture, it could also be used for assessment of future risks.

Figure 2.A1.12. A physiographic approach to water quality risks in the Southland Region of New Zealand

Left panel: Determination of the physiographic units, middle panel zone at risk in the Mataura PU, right panel mechanism of groundwater nitrate contamination on site



Source: Presentation by B. Chamberlain and P. Ross (2015).

A research project in Switzerland has also used advanced targeting to assess and manage water risks for agriculture in two very specific locations (Fuhrer et al., 2013). As explained in Box 2.A1.2, the project was designed to identify sustainable adaptive management of land and water under climate change. The conclusions highlight the benefits of a highly targeted approach. Although Switzerland is generally considered a water-abundant country, Switzerland is expected to face localised agriculture water risks. The case study hotspot approach is helpful to understand how local adaptation can be effective at any level, but the authors also note that results from the two regions should not be used for generalisation.

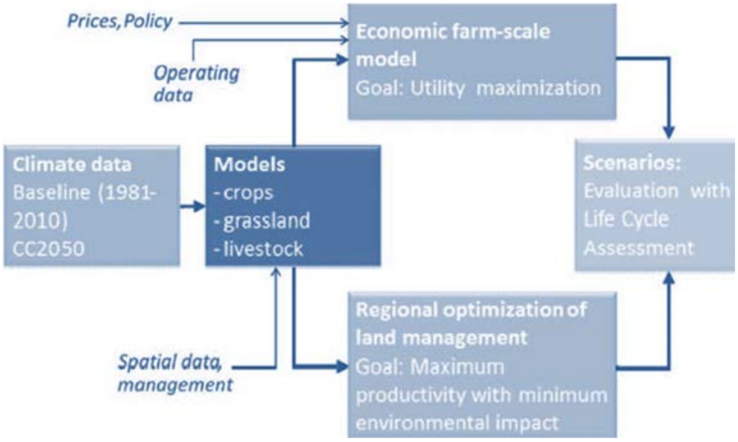
These examples demonstrate both the diversity and usefulness of the hotspot approach to assess water risks in agriculture at a various scales. They also pinpoint some of the challenges to determine future water risk hotspots. Most do not incorporate future projections; however, those that do, focus on particular risks (climate change, generally not competing demand factors) or do not focus on agriculture. Furthermore, most approaches involve a combination or cascade of models, each with different assumptions, datasets and scenarios.

Box 2.A1.2. Adaptive management of land and water to mitigate the risks of climate change: A study of two river catchments in Switzerland

Climate change models suggest that there will be a higher crop water requirement and lower water soil availability in summer months in Switzerland. Agriculture will therefore further call upon irrigation, and water course and lake water may face availability constraints. Management solutions are needed to ensure that agriculture can be maintained under increasing water pressure. Broad-based solutions may not be efficient or effective in Switzerland given the country's mountainous topography, which defines the land's hydrology and the pattern of agriculture activities,. Targeted actions may be more likely to lead to optimal results.

To this effect, two agriculture catchment were selected–the Broye and the Greifensee regions–both with similarities and differences. Both regions' agriculture support crop cultivations (including field crops and potatoes) in the lowlands and dairy production in the higher lands, but the Broye region's catchment broadly uses irrigation to support crops and livestock in summer, while the Greifensee region only uses irrigation for vegetables when necessary.

Figure 2. A1.13. Components of the model used for regional optimisation of land and water resources under climate change



Source: Fuhrer et al. (2013).

A combination of analytical methods was applied to assess current and future constraints and simulate scenarios to respond to the prevalent risks in the two regions (Figure 2.A1.13). A common database with climate information, spatial data, and region-specific management was used to build models at the farm and regional levels that incorporate results from a component model capturing the effect of climate on crop and livestock activities. Life cycle assessment was used to investigate the broader environmental impacts of identified strategies.

The study shows that locally adapted regional plans can help optimise results in the two regions. In the Broye region, this may imply focusing irrigation on the most suitable areas for crops in lowland areas and not irrigating other pasture but instead using crops that are adapted to the climate. The authors also find that at the farm level, there is a trade-off between increased profitability (and often decreasing non-water related environmental impacts) and increasing water stresses regionally. The results further show that (1) changes in farm structures, spatial organisation of crops and farm management practices can, with acceptable production loss, substantially reduce the water needs of a farm, and (2) it is possible to decrease the water needs through implementation of policies such as volumetric water pricing or water quota with relatively small impact on farm income.

Source: Fuhrer et al. (2013).

Annex 2.A2

Additional information on the water risk hotspot selection

2.A2.1. Water risk assessment: Data and method

Measurements of water risks are based on a database of 118 observations from 64 studies. The 64 studies were selected via Google Scholar research (general key words future water risk and agriculture, plus more advanced key words on quality, salinity etc.), snow ball references and additional publications proposed by delegations. The studies are the following : ADRC (2016); Alavian et al., (2009); Alcamo et al. (2007); Arnell (2004); Baettig et al. (2007); Bates et al. (2008); Bijlsma et al. (1996); Brakenridge (2016); Brauman et al. (2016); Cosgrove and Cosgrove (2012); de Sherbinin (2014); Döll (2002); Döll (2009); Elliott et al. (2014); Fischer et al. (2007); Fraser et al. (2013); Frenken and Gillet (2012); Fung et al. (2011); Gassert et al. (2013); Gerten et al. (2011); Giorgi (2006); Gleeson et al. (2012); Haddeland et al. (2014); Hanasaki et al. (2008); Hejazi et al., (2014); Hirabayashi et al. (2013); IFPRI and Veolia (2015); Ignaciuk et al. (2015); IPCC (2012); Jiménez Cisneros et al. (2014); Kiguchi et al. (2015); Liu et al. (2014); Luck et al. (2015); Luo et al. (2015); Mekonnen and Hoekstra (2016); Mendelssohn et al. (2012); Milly et al. (2005); Murray et al., (2012); Nicholls and Cazenave (2010); Nicholls and Tol (2006); Nicholls et al. (1999); OECD (2015c); Parish et al. (2012); Pfister and Bayer (2013); Piontek et al. (2013); Reager et al. (2016); Ringler et al. (2011); Rockström et Karlberg (2009); Rockström et al. (2009); Rowley et al. (2007); Sadoff et al. (2015); Scheffran and Battaglini (2011); Schewe et al. (2013); Shen et al. (2010); Shen et al. (2014); Siebert et al. (2010); Van Drecht et al. (2009); Van Puijenbroek et al. (2014); Villholth et al. (2014); Vörösmarty et al. (2000); Wada et al., (2012 and 2013); WWF (2016); and 2030 WRG (2009).

Observations all report the degree of water risk of different regions or countries at the global scale using different methods. Studies include measurements of changes in: climate change instability hotspots, climate vulnerability index, consumption to Q90 ratio, cumulative absorption/demand ratio, cumulative supply to demand ratios, dry days, emissions of BOD, N and P, extreme storms, flood damages, flood frequency, flood risks, groundwater depletion, human vulnerability to climate change induced decreased groundwater resources; irrigation water demand, irrigation requirements, irrigation water reliability, N and P sewage emissions; coastal land loss from sea level rise, nutrient discharge levels, population, water use and climate impacts, precipitation intensity, pressure on water resources, probability of warm, streamflow, regional climate-change indices, renewable water abundance; runoffs, sea level rise affecting agriculture land, soil moisture, threshold temperatures for significant effects on discharge, water-demand supply gaps, water availability of green plus blue water, water scarcity; water stresses indices (multiple); wet or dry years; withdrawal to available water ratios.

The normalisation of measurements is done by categorical ranking of leading countries at risk to reflect the purpose of the hotspot identification exercise (only areas most at risk matter). The diversity of measurements, therefore, does not prevent the analysis; instead, it allows both covering multiple risk dimensions and increasing the robustness of the identification exercise. The underlying assumption of the assessment is that if a country or region is found to be among the top future water scarcity risks by multiple indices, it is more likely to be facing such water risks, than if a few studies using one method or projection find it at risks.

Care was taken to only take results from scenarios with no simulated response as much as possible (e.g. water risk adaptation or mitigation of risk), so the assessments generally use business as usual or no action scenarios.

Countries and economies with separated measurements are: Afghanistan, Algeria, Angola, Argentina, Armenia, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belgium, Benin, Bhutan, Plurinational State of Bolivia, Botswana, Brazil, Bulgaria, Burkina Faso, Burundi, Cambodia, Cameroon, Canada, Central African Republic, Chad, Chile, China (People's Republic of), Colombia, Costa Rica, Côte d'Ivoire, Cuba, Czech Republic, Democratic People's Republic of Korea, Democratic Republic of the Congo, Denmark, Djibouti, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Estonia, Ethiopia, Finland, Former Yugoslav Republic of Macedonia, France, Gabon, Georgia, Germany, Ghana, Greece, Guatemala, Guyana, Guinea-Bissau, Honduras, Hungary, Iceland, India, Indonesia, Islamic Republic of Iran, Iraq, Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Korea, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Latvia, Lebanon, Liberia, Libya, Luxembourg, Madagascar, Malawi, Malaysia, Mali, Mauritania, Mexico, Republic of Moldova, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, Netherlands, New Zealand, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russian Federation, Rwanda, Saudi Arabia, Senegal, Serbia, Slovak Republic, Slovenia, Somalia, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Chinese Taipei, Tajikistan, Tanzania, Thailand, Togo, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, United Arabic Emirates, United Kingdom, United States, Uruguay, Uzbekistan, Bolivarian Republic of Venezuela, Viet Nam, Western Sahara, Yemen, Zambia, and Zimbabwe.

For each observation, countries ranked in the high or highest category are considered at risk (in the text and/or in a map or figure), and attributed a value of one for the index representing the specific measurement. This is done for 142 countries found to have some measurement of risks (and ASEAN, OECD, and Mediterranean countries). For observations that target groups of countries, large regions or continents, a value of one is attributed to all the countries in the region.

The individual observations are then summed by category of risk (shortage, quality etc.) and type of measurements (present, past) for each country for the entire database. These numbers are then divided by the relevant total observations to obtain the relevant indicator (total, current, future water risk, etc.). They are then crossed by agriculture shares of commodity production from the IMPACT and AgLink-Cosimo projections.

2.A2.2. Supplementary data from the hotspot identification exercise

Table 2.A2.1. Number of studies reporting specific water risks by country in the reviewed studies

	Total future	Total shortage future	Total excess future	Total variability future	Total quality future
China (People's Republic of)	59	43	13	2	1
United States	53	42	6	3	2
India	49	34	13	0	2
Algeria	42	39	1	2	0
Mexico	40	36	0	3	1
Morocco	39	36	1	2	0
South Africa	39	36	1	1	1
Australia	36	29	5	1	1
Pakistan	36	28	6	0	2
Chile	35	34	1	0	0
Israel	35	34	1	0	0
Tunisia	35	32	1	2	0
Iran	34	33	1	0	0
Jordan	34	33	1	0	0
Lebanon	34	33	1	0	0
Libya	34	31	1	2	0
Spain	34	31	0	3	0
Syria	34	34	0	0	0
Argentina	33	24	8	0	1
Turkey	33	32	1	0	0
Egypt	32	28	2	2	0

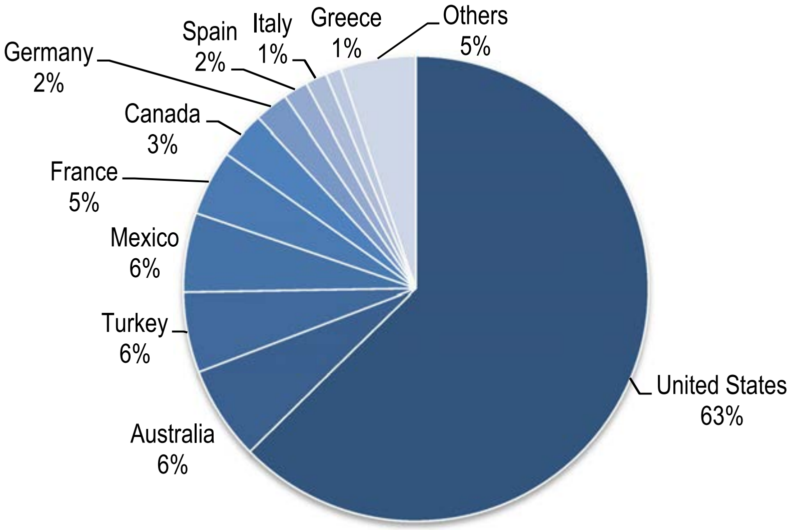
Greece	29	28	0	1	0
Iraq	29	28	1	0	0
Kuwait	29	28	1	0	0
Namibia	29	26	1	1	1
Peru	29	21	8	0	0
Afghanistan	28	27	1	0	0
Brazil	27	22	4	0	1
Italy	27	24	1	2	0
France	26	24	0	2	0
Saudi Arabia	26	22	4	0	0
Mozambique	25	20	3	1	1
Qatar	25	21	4	0	0
United Arab Emirates	25	21	4	0	0
Uzbekistan	25	24	1	0	0
Viet Nam	25	13	11	1	0
Uganda	24	18	4	1	1
Canada	23	11	8	3	1
Senegal	23	18	3	1	1
Yemen	23	20	3	0	0
Zimbabwe	23	21	0	1	1
Armenia	22	21	1	0	0
Kazakhstan	22	21	1	0	0
Thailand	22	12	9	1	0
Azerbaijan	21	20	1	0	0
Cambodia	21	9	11	1	0
Ethiopia	21	13	6	1	1
Georgia	21	20	1	0	0
Indonesia	21	8	11	2	0
Russia	21	11	9	1	0
Tajikistan	21	20	1	0	0
Portugal	20	20	0	0	0
Turkmenistan	20	19	1	0	0
Eritrea	19	12	5	1	1
Guatemala	19	15	1	3	0
Honduras	19	15	1	3	0
Kenya	19	12	5	1	1
Kyrgyzstan	19	18	1	0	0
Madagascar	19	14	3	1	1
Nicaragua	19	15	1	3	0
Tanzania	19	12	5	1	1
Venezuela	19	16	2	1	0
Angola	18	13	3	1	1
Costa Rica	18	14	1	3	0
Malawi	18	16	0	1	1
Myanmar	18	6	11	1	0
Nigeria	18	12	4	1	1
Somalia	18	11	5	1	1
Botswana	17	15	0	1	1
Bulgaria	17	17	0	0	0
Burkina	17	12	3	1	1
El Salvador	17	13	1	3	0
Germany	17	14	1	1	1

Former Yugoslav Republic of Macedonia	17	17	0	0	0
Panama	17	13	1	3	0
Philippines	17	7	9	1	0
Colombia	16	9	6	1	0
Rwanda	16	10	4	1	1
Western Sahara	16	12	4	0	0
Benin	15	11	2	1	1
Bolivia	15	12	3	0	0
Burundi	15	9	4	1	1
Djibouti	15	9	4	1	1
Ghana	15	10	3	1	1
Lao PDR	15	7	7	1	0
Malaysia	15	4	10	1	0
Mauritania	15	11	4	0	0
Sudan	15	11	4	0	0
Bangladesh	14	4	9	0	1
Cameroon	14	9	3	1	1
Chad	14	8	4	1	1
Cote d'Ivoire	14	9	3	1	1
Gabon	14	9	3	1	1
Togo	14	10	2	1	1
Zambia	14	12	0	1	1
Central African Republic	13	8	3	1	1
Democratic Republic of the Congo	13	9	2	1	1
Ecuador	13	7	6	0	0
Guinea-Bissau	13	9	2	1	1
Mali	13	9	4	0	0
Niger	13	8	5	0	0
Papua New Guinea	13	4	8	1	0
Romania	13	13	0	0	0
Korea	13	5	5	3	0
Equatorial Guinea	12	7	3	1	1
Poland	12	10	1	0	1
United Kingdom	12	8	3	1	0
Belgium	11	10	0	1	0
Japan	11	3	5	3	0
Netherlands	11	10	0	1	0
Serbia	11	11	0	0	0
Austria	10	8	1	0	1
Czech Republic	10	8	1	0	1
Hungary	10	8	1	0	1
Slovak Republic	10	8	1	0	1
Slovenia	10	8	1	0	1
Switzerland	10	8	1	0	1
Ukraine	10	10	0	0	0
Nepal	9	7	1	0	1
Paraguay	9	8	1	0	0
Sri Lanka	9	4	4	0	1
Uruguay	9	2	7	0	0
Guyana	8	6	1	1	0
Moldova	8	8	0	0	0
Cuba	7	5	0	2	0

Liberia	7	4	3	0	0
Norway	7	1	6	0	0
Denmark	6	3	3	0	0
Sweden	6	1	5	0	0
Chinese Taipei	6	2	3	1	0
Bhutan	5	2	2	0	1
Dominican Republic	5	3	0	2	0
Finland	5	2	3	0	0
Democratic People’s Republic of Korea	5	1	2	2	0
Luxembourg	5	4	1	0	0
Belarus	4	4	0	0	0
Estonia	4	1	3	0	0
Latvia	4	1	3	0	0
Ireland	4	4	0	0	0
Mongolia	3	1	2	0	0
New Zealand	2	0	1	0	1
Iceland	0	0	0	0	0

Source: Review of the 64 studies.

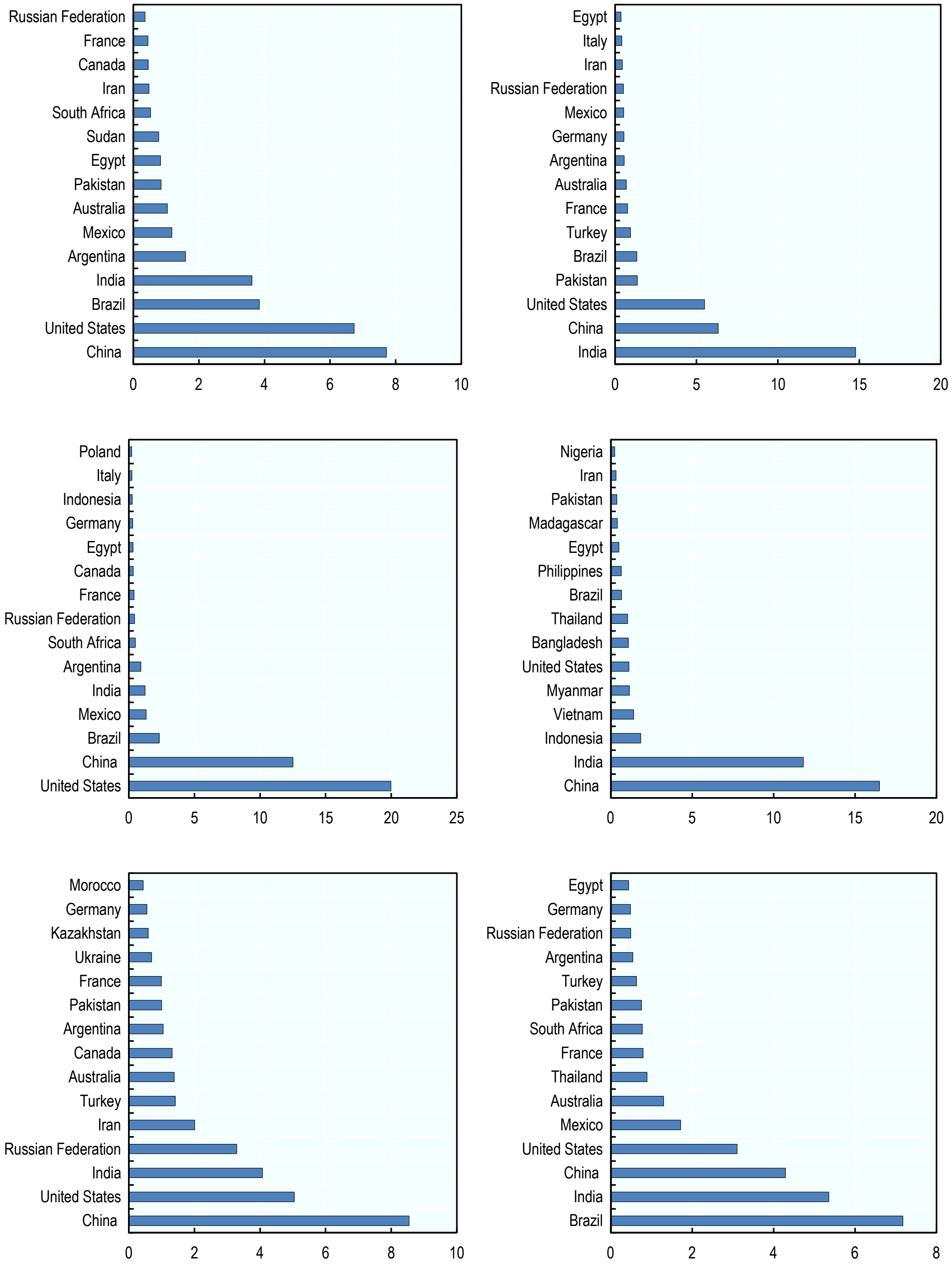
Figure 2.A2.1. Future agriculture water risk indices by OECD country, 2024-50 average (8 commodities)



Source: Author’s own work based on computations using AgLink-Cosimo, IMPACT and the review of 64 publications.

Figure 2.A2.2. Future water risk hotspot by commodity (2050) (1)

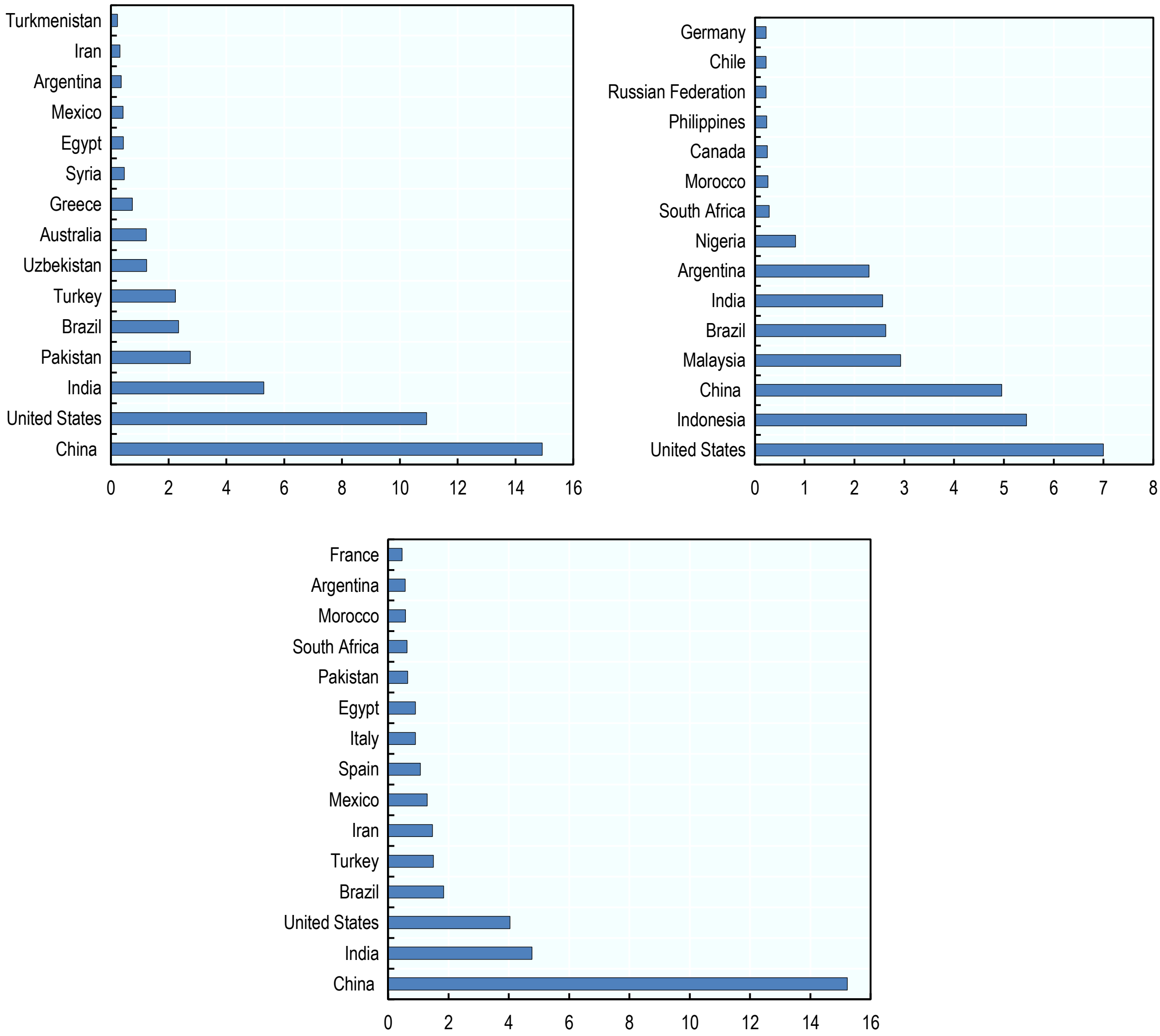
Top left: Beef, Top right: Dairy, Middle left: Coarse grains, Middle right: Rice, Bottom left: Wheat, Bottom right: sugar



Source: Author's own work, derived from IMPACT projections and the water risk analysis.

Figure 2.A2.3. Future water risk hotspots by commodities (2050) (2)

Top-left: cotton, top right: oilseeds, bottom: fruits



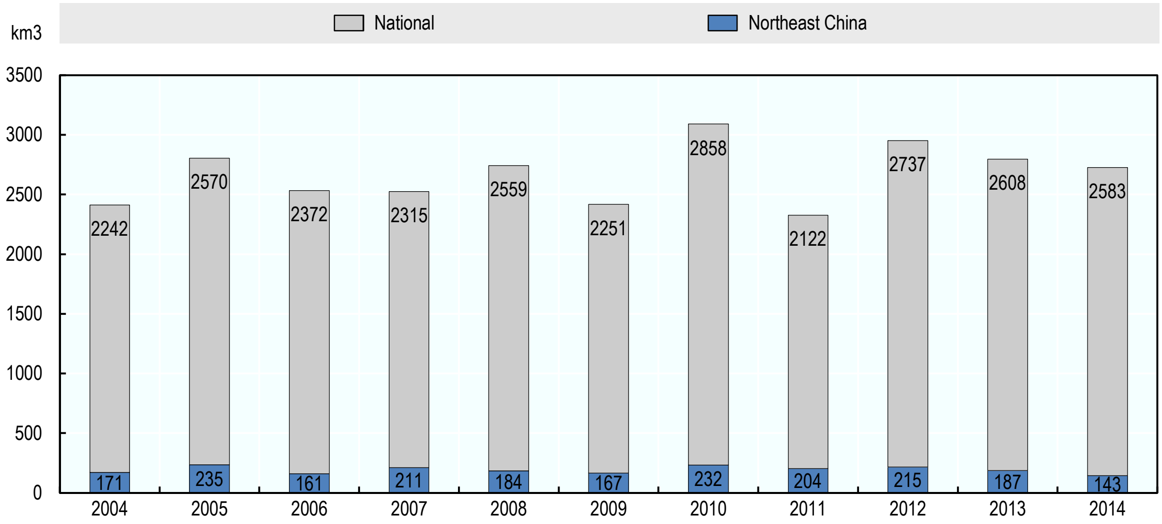
Source: Author's own work, derived from IMPACT projections and the water risk analysis.

2.A2.3. Supplementary information on Northeast China and Northwest India[5]

The case of Northeast China

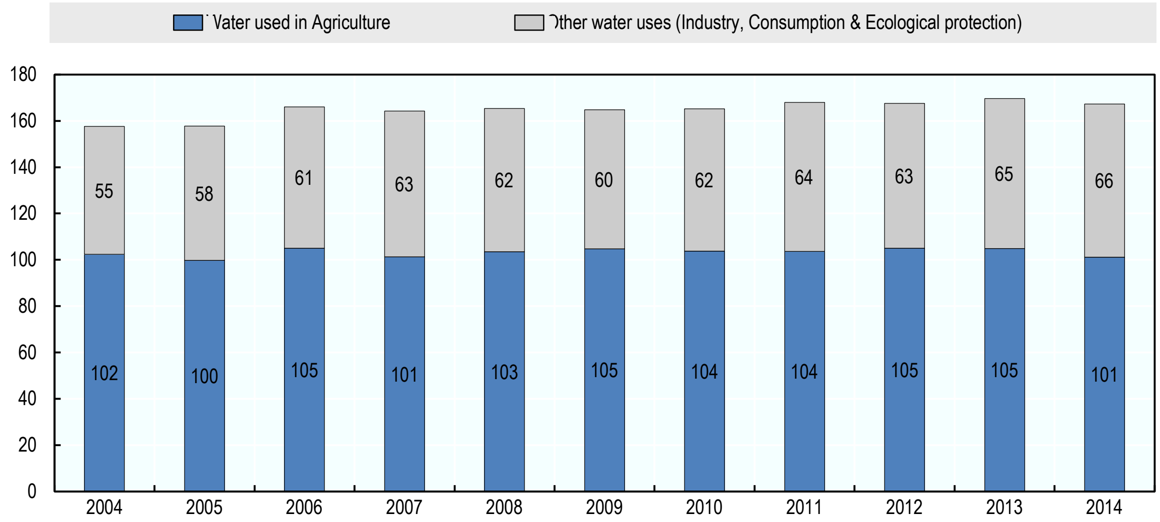
Recent trends on water and agriculture

Figure 2.A2.4. Evolution of estimated water resources in China and the Northeast Region, 2004-14



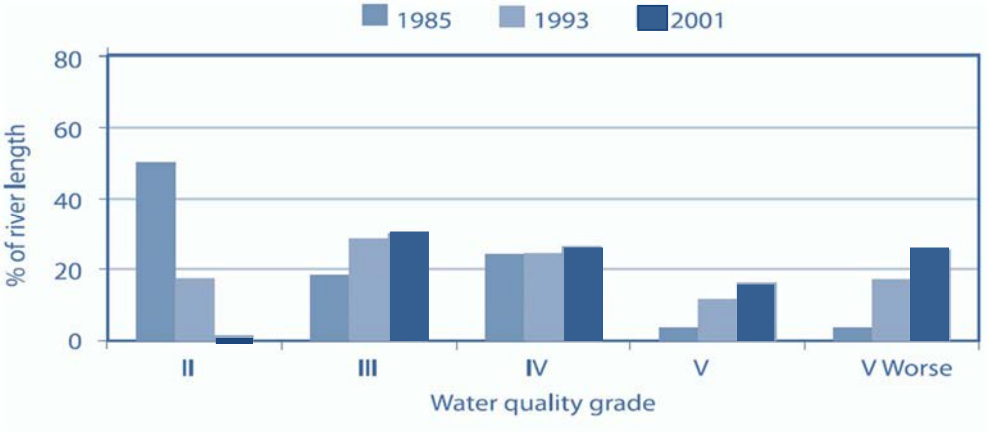
Source: National Bureau of Statistics of China (2016).

Figure 2.A2.5. Agriculture and total water use in Northeast China, 2004-14 (km3)



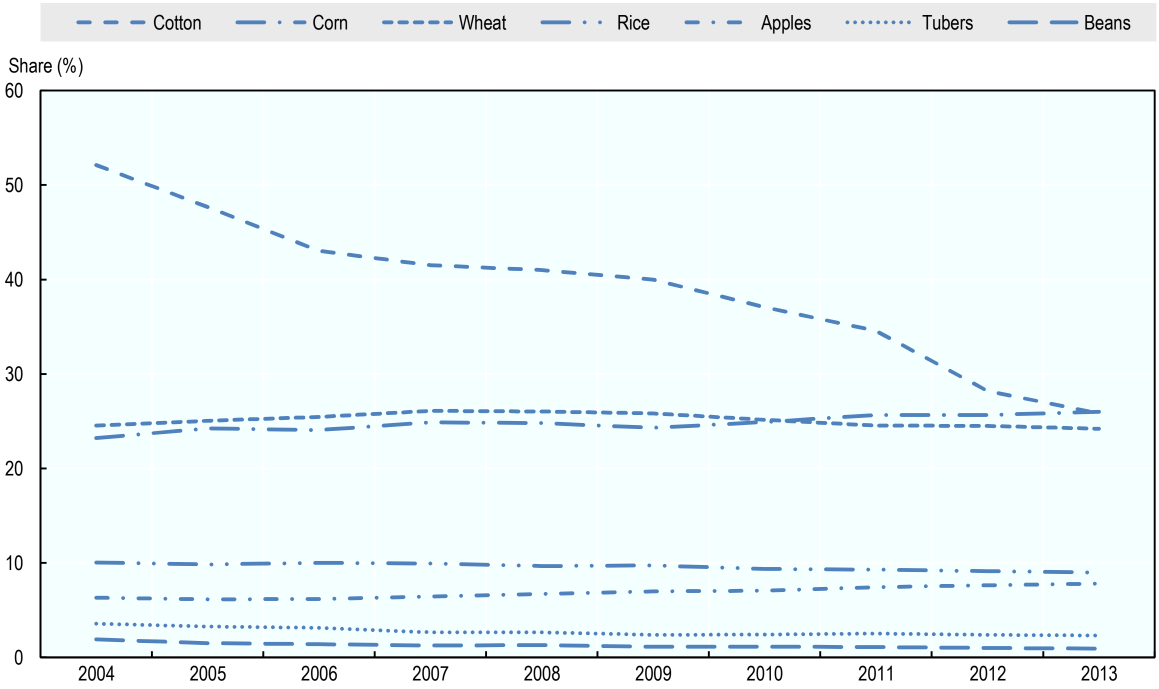
Source: National Bureau of Statistics of China (2016).

Figure 2.A2.6. Yellow River water quality, 1985, 1993 and 2001



Source: Giordano et al. (2004).

Figure 2.A2.7. Regional share of production by crop for Northeast China, 2004-13



Source: National Bureau of Statistics of China (2016).

Water conditions in the mid to late century

A first determinant of the Northeast's future water resources–climate change–may have varied effects. On the one hand, higher precipitation levels may ease water scarcity concerns over the next century. Some climate change projections point towards increase of summer precipitation (Piao et.al, 2010). In the Huang-Hai Plain (Beijing, Tianjin, Hebei and Shandong) annual precipitation is projected to increase 200 to 300 mm (A2 scenario) or 150 to 240 mm (B2 Scenario) by 2085 (Thomson et al., 2006).

Rising temperatures on the other hand may have a negative effect on water availability due to increased evaporation. Temperatures have increased 0.5°C to 0.8°C over the last century (Ding et al, 2007; PRC, 2007) and are projected to continue to rise 2-4°C in Asia (2046-2065) and 4-6°C in the long-term (2081-2100) (Hijoka et al., 2014). For the Huang-Hai Plain, maximum and minimum temperatures are projected to increase 0.5°C to 2°C by 2030 and 2.5°C and 5°C by 2085 (Thomson et al., 2006). Evaporation for the Huang He basin is predicted to increase between 15 and 49% in 2080 (Zhang et al., 2007).

Water supplies may also be affected by climate change through waning glaciers. 5% to 27% of the area covered by glaciers in China is predicted to disappear by 2050 and 10% to 67% by 2100 (NARCC, 2007). Both the retraction and seasonal melting of these glaciers are expected to impact freshwater levels in Northeast China. In the short run, it will likely contribute to a surge in annual runoff from major rivers. In the long run, water storage may be significantly reduced. Additionally, the rise in sea level could accelerate– increasing water salinity in rivers and aquifers in the (Buckley, 2015). This could imply increases in salinity and land losses.

Estimations of the Northeast’s future water supply decrease further if water quality declines. As industry expands, water quality is expected to further deteriorate due to rising pollution levels. China’s pollution levels are predicted to increase; high emissions of chemical oxygen demand (COD) are projected to reach 100 million tonnes by 2050, 80 million tons more than the 2030 targets (World Bank, 2013a). As 70% of the rural North China Plain’s groundwater is already too polluted to be suitable for human use (China Water Risk, 2016) future pollution is a serious concern.

The challenge of water scarcity may be further compounded as demand for water increases across China; water demand is projected to increase 532 billion cubic metres (61%) from 2005 to 2030 (2030 Water Resource Group, 2009). China’s water deficit specifically for agriculture demand in 2030 is predicted to be 43.1 billion cubic metres, of which 91% will be needed for irrigation (Lui, 2006).This upward trend may be driven by a number of factors, including: rapid economic development, population growth and urbanisation. Although China’s growth rate is projected to decrease in the coming decades, GDP growth is still predicted to remain at 5% in 2030 (World Bank, 2013a). The continued economic growth will expand China’s middle class, triggering higher demand for a larger variety in goods and food (World Bank, 2013a). Competition for water resources may also increase from China’s growing population until it peaks at 1.4 billion in 2030 (UNDESA, 2015). Municipal and domestic water use is also likely to rise as the urban population swells from 56% in 2015 to 76% in 2050 (UNESCO, 2010).

With similar socioeconomic and demographic trends over the last 15 years (National Bureau of Statistics of China, 2016), the Northeast’s water demand is likely to mirror national projections. Projections suggest rising demand will trigger a total blue water deficit of 20 to 80% of demand in the Huang-He and Hai basins and 0 to 20% in the Huai basin by 2030 (2030 Water Resource Group, 2009).

The Northeast’s water demand is predicted to increase across all sectors (Table 2.A2.2). The agriculture sector will remain the largest user by far, but it will increase at a slower rate than the industry and municipal sectors (Xie et al., 2008). Demand from the Northeast’s industrial sector is predicted to increase between 24% and 39%, exceeding the national average of 20% (Xie et al., 2008). The largest source of this demand in most of the Northeast is currently thermal power cooling, which may decline given the Chinese government’s plan to increase nuclear, wind and solar power generation by 2050. The total water reliance of planned installed capacity is projected to decrease from 100% in 2005 to 70% in 2050 (China Water Risk, 2015). Municipal and domestic demand is also predicted to increase at an accelerated rate. Although the smallest share of water demand comes from the municipal and domestic demand in 2000, it is predicted to almost reach up to more than 20% in some areas by 2030 (Xie et al., 2008). This growing demand for municipal and industrial use will further increase the water stress in the agriculture sector.

Given declining surface water availability and rising demand in the Northeast, current groundwater depletion seems unrecoverable (Cao et al., 2013). Expansion of groundwater irrigation area has continued in the North, with the share of groundwater irrigation rising from 58% in 1995 to 84% in 2012 (Wang, 2017). Intensification of groundwater use has also resulted in lowering water tables. A study of 400 villages in northern China shows for instance that the share of villages with water tables dropping by more than 25cm a year increased from 49% to 63% from the period 1995-2004 to 2006-2016 (Ibid.).

Table 2.A2.2. Current and projected water demand by sector and basin

River basins	Total demand (km3)			Per capita demand (m^3)		Share by sector (%)					
	2000	2030	increase	2000	2030	2000			2030		
						Municipal	Industry	Agriculture	Municipal	Industry	Agriculture
Huai	65.1	71.6	6.5	332	320	10	16	74	18	20	62
Huang	43.7	48.1	4.4	397	364	7	14	79	13	19	68
Hai	40.2	42.9	2.7	312	262	13	17	70	21	21	58
Liao	19.6	22.7	3.1	356	355	13	18	69	20	25	55
China	581.2	653.5	72.3	461	432	10	20	70	16	24	60

Source: Xie et al. (2008).

At the same time, global simulations suggest that groundwater could recharge more than 30% by 2050 in several regions including northern China (Döll and Fiedler, 2008; Taylor et al., 2013). Wide-scale surface irrigation as well as future increases in precipitation could contribute to the recovery (Döll and Fiedler, 2008). Applying improved groundwater management strategies could increase storage by 50m3 by the end of 2030, although 50 more years would be needed for full recovery. If most pumping comes from recharge in the future, groundwater depletion could be avoided (Cao et al., 2013).

Future water availability may have varied implications for future agriculture production

Though limited in scope, a range of models have assessed the impact of certain changes in future water availability on agriculture production. Models focused specifically on climate change suggest that future increases in precipitation may benefit some crops, but the parallel increase in temperatures may outweigh these gains for others. Other models that do not account for climate change, suggest that water stress will increase and negatively impact production across the board. The challenge in aggregating these results is that different assumptions limit comparability across models (Wang et al., 2014). Most studies do not account for factors such as increasing pests and diseases due to higher temperatures, the impact of adaptation measures (Piao et al., 2010), and the possible effect of CO2 fertilisation (Xiong et al., 2010). Most importantly, declining resources due to deteriorating water quality and rising demand are not included in most models (e.g. Chavas, 2009; Chen et al., 2016).

Keeping these limitations in mind, water scarcity is likely to remain an important constraint for agriculture productivity growth. On the supply side, climate change may benefit certain crops through rising precipitation, but hurt others through rising temperatures. The reduction in long term water storage in glaciers from climate change may also negatively impact future agriculture production in the long run. Moreover, future increases in run-off may exacerbate soil erosion and thus reduce water retention; the loss of top soil, which contains about 75% of vital plant nutrients (Young, 1989), is a key concern for agriculture production. Furthermore, declining water quality in the Northeast may further constrain water access for agriculture production. Of course, some relief may be provided by infrastructure projects such as the South-North water diversion project to increase water supplies in the North.

On the demand side, rising competition for water resources is likely to negatively impact agriculture production. Urbanisation and a growing population with higher incomes will not only increase the direct demand for water but also for water-intensive industrial goods and food products. Rising incomes may also change food consumption patterns towards highly processed goods, such as meat, and thus may motivate farmers to increase water-intensive production of livestock. On the other hand, water efficiency gains—due to improvements in on-farm irrigation technology as well as efficiencies of scale through China's shift towards land consolidation—may ease production requirements for the agriculture sector.

Though not all of these factors are taken into account—studies generally do not account for water demand from other sectors, groundwater use, or other issues—several projections are also available for specific crops, with mixed results (Wang et al., 2014). Chavas et al. (2009) suggest that rice, wheat and maize yields will increase significantly; however, this result could be inflated by their assumptions about CO2 fertilisation effects (Hare et al., 2011). Other studies paint a more nuanced picture. According to Hijoka et al. (2014), rising precipitation will not be enough to offset the negative impact of higher temperatures on rice yields. Tao et al. (2009) predict that corn yields in the North China Plain will also decrease (by 9.1% to 9.7% by 2020, 15.7% to 19.0% by 2050 and 24.7% to 25.5% by 2080). However, wheat production, especially winter wheat, could increase in the Huang-Hai Plain due to rising temperatures and precipitation (Hijoka et al., 2014; Xiong et al., 2010). Without these positive climate effects, however, wheat could be negatively affected in the future (OECD, 2015c). Given the high productivity rates and low water requirements, future potato production may also increase (Chavas et al., 2009).

The case of Northwest India

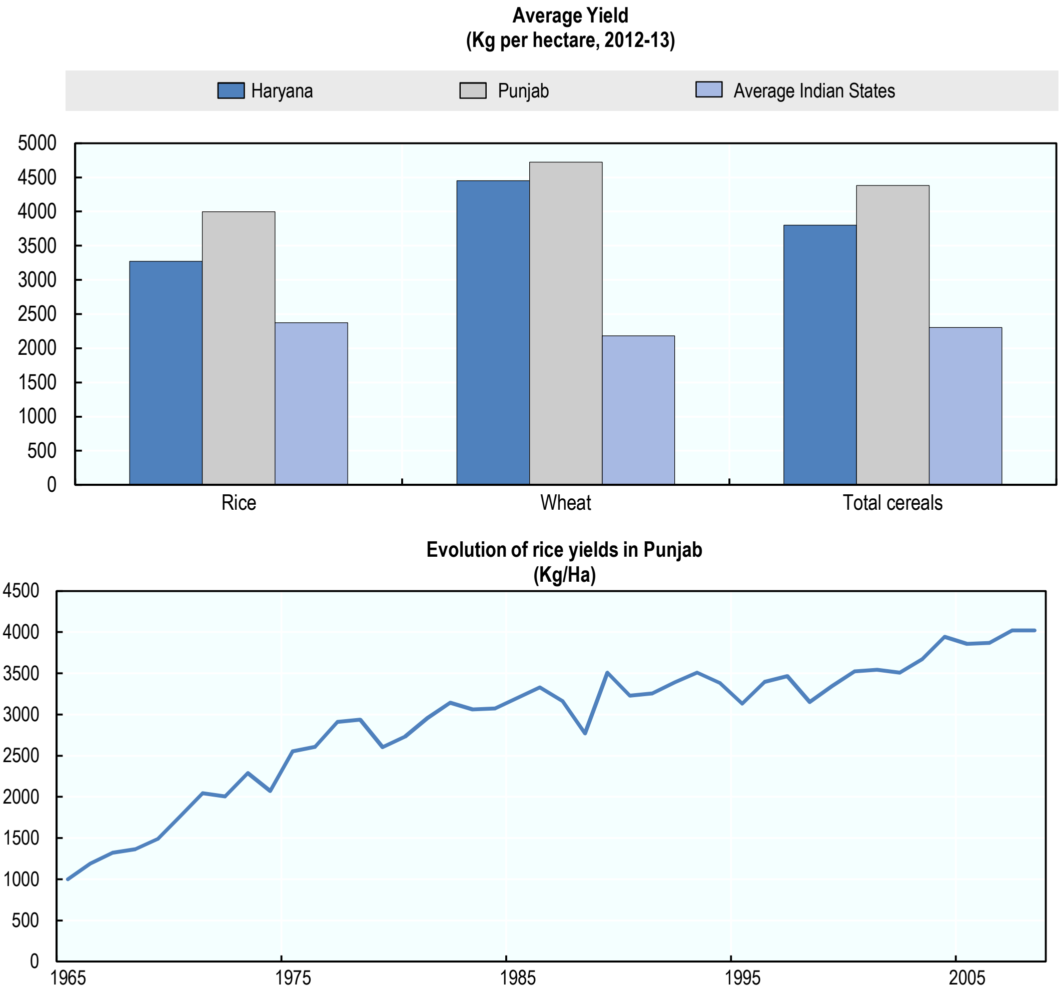
Agriculture and groundwater depletion

Punjab and Haryana are agriculture strongholds in India. The two states account for only 3% of the national territory, but produce 15% of its rice and 30% of its wheat (Ministry of Statistics and Program Implementation, 2016c). They achieve the highest yields in the whole country both for rice and wheat. A hectare of cultivated land in Haryana or in Punjab produces more than twice more wheat as an average hectare of cultivated land in India (Figure 2.A2.8). In the two states, the income of the majority of the population relies directly on agriculture (Bhupal, 2012; Punjab Directorate of Agriculture, 2016).

Groundwater use is intensifying in Punjab. Until the end of the 1990s, the share of croplands under tubewell irrigation in Punjab increased rapidly. Simultaneously, yields for major crops entered a period of stagnation (World Bank, 2013b; Rang et al., 2014). At the beginning of the 2000s, the area under groundwater irrigation hit a plateau, and even slightly decreased between 2001 and 2012 (Figure 2.A2.9). In spite of this, groundwater development[6] continued to rise. Thus, the recent worsening of the groundwater depletion is not generated by an extended access to tubewell irrigation, but by the growing intensity of water pumping (Figure 2.A2.10).

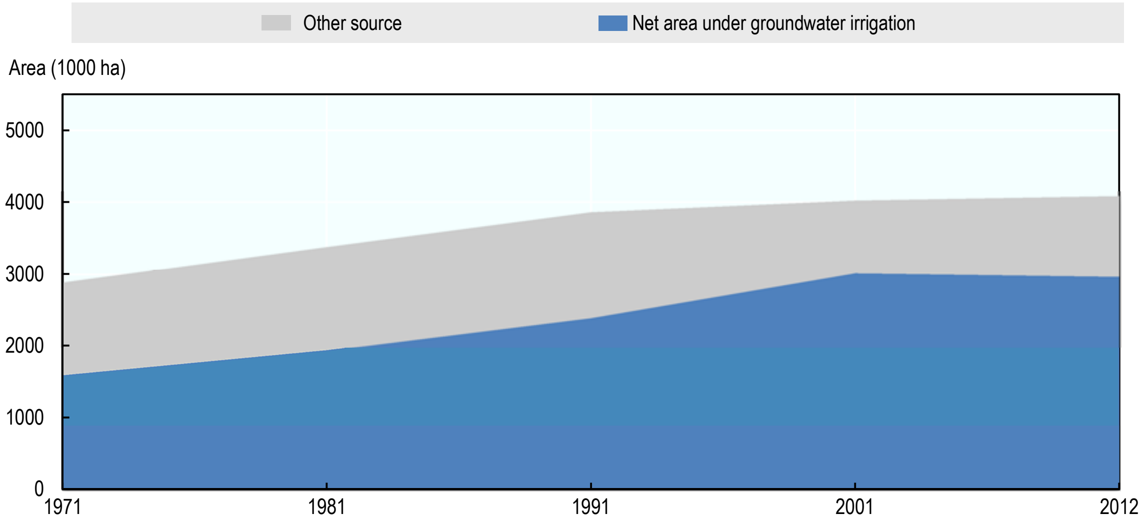
Figure 2.A2.8. A productive grain production region

Top: Average yields (kg/ha) for major crops in Punjab and Haryana, compared to nationwide; Bottom: evolution of average rice yields in Punjab



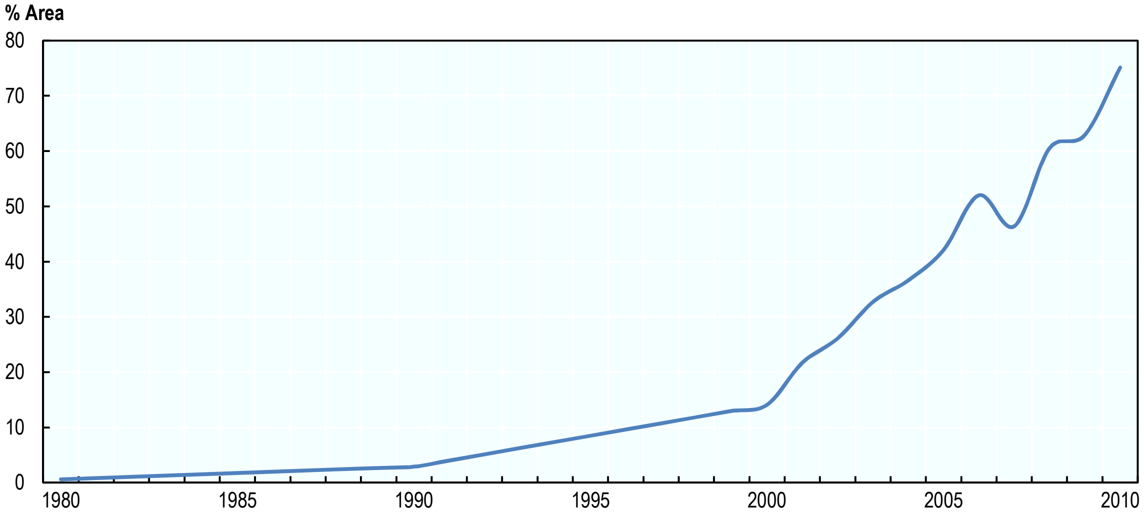
Source: Ministry of Statistics and Program Implementation (2016c); Rang et al. (2014).

Figure 2.A2.9. Evolution of irrigated area by source in Punjab, India



Source: Agricultural Census; Singh and Singh-Bhangoo (2013).

Figure 2.A2.10. Proportion of area with groundwater depth exceeding 15m in Punjab, India



Source: CFAPPS (2013).

Expected water situation in the next decades: A growing water supply-demand gap

While most of the region is already under water stress and groundwater resources are overexploited, water demand is still expected to grow in the upcoming decades. If the cropped area seems to have reached a plateau in this region, and a further expansion of net irrigated area is unlikely (GIST Advisory, 2013), demography dynamics, urban and industrial development will put further pressure on water allocation. In India, total water demand is expected to increase by 32% by 2050 (Amarasinghe et al., 2008). Changes in temperature and precipitation patterns could also increase the groundwater needs for irrigation.

By 2050, the industrial and domestic sectors will account for 84% of the additional water demand over India (Amarasinghe et al., 2008). Punjab is currently the State with the lowest share of non-agriculture groundwater use. Haryana is the third lowest. However, with a rising population and changing consumption patterns, domestic and industrial uses are taking greater importance. In the next ten years, the region will gain

5.8 million new inhabitants, and the urban population will rise by 43% (National Commission on Population, 2006). Between 2004 and 2011, non-agriculture draft already rose from 2% to 6% of total groundwater use in Haryana (CGWB, 2006), and by 2025 Punjab projects a rise by 38% for domestic and industrial groundwater consumption compared to 2011 (CGWB, 2014).

Climate change projections point towards extreme heat and water scarcity, with land suffering higher soil moisture deficits and increased evapotranspiration, which will increase the need for irrigation during the summer and the Rabi seasons (World Bank, 2013b; Bruinsma, 2003). Temperatures are projected to rise from 1.5 ºC to 2.5ºC by 2030, and by 2 ºC to 6.5ºC by 2080 in Haryana according to various scenarios (CCAFS and CIMMYT, 2015). Global and regional climate projections show more intense precipitations in Northwest India, which will increases the risk of floods (Döll, 2002; Gosain et al., 2001), but the adverse effects caused by higher temperatures and changes in rain concentration patterns will overwhelm the potential benefits of increased precipitation over the year (Döll, 2002; IPCC, 2008).

Due to its semi-arid climate, the Indo-Gangetic plain is naturally exposed to salinity risks. Intensive groundwater pumping extents and amplifies the phenomena, which limits irrigation sources for farmers in affected areas (CGWB, 2015). According to BGS (2015), increasing salinity caused by groundwater abstraction and intensive irrigation in the region could be a bigger threat than falling water tables. Salinity limits water uptake capacity of plants, and dramatically decreases yields for most of the crops (Shrivastava and Kumar, 2014). Almost 0.5 million hectares are already affected by salinity in the State of Haryana, and this surface is expected to grow in the coming decades, following the patterns of groundwater depletion (Kim, 2013). In Punjab, salinity problems from the Southwest (on a surface representing 40% of the State) are now extending to the central districts (Mahajan et al., 2012). By 2023, in some central districts of Punjab, water tables will sink beyond 50m depth. Today the groundwater of these regions is still fresh, but forecasts estimate that water salinity will increase because of pumping-induced reverse flows coming from surrounding brackish aquifers (Hill-Clarvis et al., 2016; Mahajan et al., 2012). In addition, the mobilisation of deeper and more saline water through tubewell irrigation affects the quality of shallow waters (BGS, 2015). Finally, there is evidence of pollutant breakthrough and water leakage to the deep reservoirs of the multi-layered aquifers, due to intensive pumping (Lapworth et al., 2014).

Future industrialisation also raises concerns about development of groundwater pollution. Indeed, sewage water is commonly used for field irrigation and fertilisation; but in Punjab, 60% to 70% of industrial effluents are discharged in sewage drains without any treatment. Therefore, in the vicinity of large cities and factories, soils and groundwater get contaminated with anthropogenic pollutants such as mercury, lead, and other toxic metals (Aulakh et al., 2009). Domestic and drinking purposes are the first hit by these contaminations and in some areas, groundwater has also been declared unfit for irrigation (Singh, 2001). Groundwater monitoring authorities support recycling of industrial effluents as a way to minimise both groundwater withdrawal and pollution (Pandey, 2011).

Climate change projections announce significant changes that will adversely affect the hydrological situation in southern Asia. In the future, intra-seasonal climate variability will be exacerbated, and the risk of unexpected drought will increase (World Bank, 2013b). Empirically, the latest unusually dry cropping seasons have led to higher groundwater uptakes to compensate surface water and soil moisture deficit. Therefore, aquifers will be more and more solicited as reliable water reservoirs to answer hydric stress (Krishan et al., 2015; Mohinder, 2016; IPCC, 2008). In addition, increased temperatures will decrease the water storage efficiency of surface water reservoirs and open irrigation canals, that is to say the capacity of these systems to conserve and deliver water without loss (CGWB, 2013). Besides, the Indus basin and the Ganges basin are broadly supplied by snowmelt water (PSCST, 2014). Since melting mountain glaciers are declining on the long term, rivers flows will be affected during the summer as early as 2050 (Barnett et al., 2005; World Bank, 2013b; PSCST, 2014). Finally, even if precipitations will increase in total, they will be more variable and concentrated in time during a shorter monsoon. As a result, groundwater recharge could drop if storage capacities are not improved (Bruinsma, 2003; Taylor et al., 2013).

Notes

1. Consequences may also be positive, but the word is more widely associated with a negative outcome.

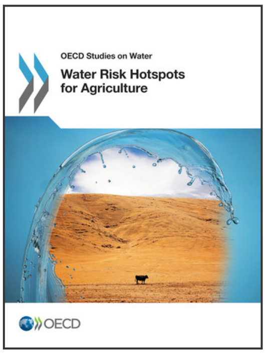
2. IPCC (2012) defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions".

3 The order of the assessment is inter-changeable; the determination of water risks may precede agriculture area, so long as they are coinciding at the end.

4. This, however, could increase flood risks.

5. Supplementary information on the case of the Southwest United States can be found in Cooley et al. (2016).

6. Groundwater development is defined as the current annual rate of groundwater abstraction divided by the mean annual natural groundwater recharge.



From:

Water Risk Hotspots for Agriculture

Access the complete publication at:
https://doi.org/10.1787/9789264279551-en

Please cite this chapter as:

OECD (2017), "Defining and identifying water risks for agriculture", in *Water Risk Hotspots for Agriculture*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264279551-4-en