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Title: Assessing agricultural systems vulnerability to climate change to inform adaptation planning: An application in Khorezm, Uzbekistan

Abstract

Agriculture is one of the most vulnerable sectors to climate change. The current vulnerability assessments through traditional fragmented sectoral methods are insufficient to capture the effects on complex agricultural systems. Therefore, the traditional methods need to be replaced by integrated approaches. The objective of this study is to propose a holistic vulnerability assessment method for agricultural systems. By aggregating both agro-ecological and socio-economic information, we develop an agricultural systems vulnerability index (ASVI) which allows for: (i) a classification of geographical units according to their vulnerability level; (ii) an identification of key determinants of vulnerability for each unit; (iii) an assessment of adaptation policy scenarios considering their effects on the sustainability of the analysed systems. The proposed method is applied in the Khorezm region of Uzbekistan – a representative irrigated agricultural region in the Lower Amu Darya river basin. A decision support tool is used to facilitate multi-criteria decision analysis, including the computation of the index and performing sensitivity analysis of the results. The assessment for Khorezm reveals significant spatial differences of vulnerability levels due to a variation of contributing factors, e.g. natural resources, water productivity, rural-urban ratio. It reveals also that feasible land and water management policies could reduce the vulnerability in Khorezm, particularly in the districts with the poorest agro-ecological conditions. Overall, the proposed method could support national and local authorities in the identification of sustainable adaptation policies for the agriculture sector.

Key words: adaptation, vulnerability, Amu Darya, integrated indicators, sensitivity, sustainability, irrigated agriculture

1 Introduction

Agriculture remains a key economic sector for many low-income countries, accounting on average for 28% of their gross domestic product (GDP) (World Bank 2013). The sustainability of agricultural systems depends on many drivers acting at multiple scales, from local to global. At a local scale, the performance of agricultural production systems depends on the availability of natural resources (soil and water in particular), climatic conditions, and several social and economic variables (availability of production factors, entrepreneurship, infrastructures). In a globalised world, local social and environmental systems are affected by exogenous drivers, which cannot be controlled or managed locally, such as national and supranational policies and markets, and climatic changes.

Undoubtedly, climate change as a global driver poses a significant threat to agriculture, particularly in arid regions. The latter are exposed to more frequent hydrological extreme events and changes in the seasonal agro-meteorological conditions, along with land degradation and desertification (Gain and Wada 2014; IPCC 2014b). The climatic changes originate from both natural phenomena and anthropogenic activities. It is evident that the solution of climate change problems should theoretically be found in the implementation of effective global policies tackling the phenomena at their origin, and in particular in the control of greenhouse gas concentrations. Following international agreements such as the Kyoto Protocol, mitigation policies have been implemented to varying extents in various countries, but they have been shown to be insufficient for controlling the trends of climatic changes. As a consequence, policy makers have shifted their focus from attempting to mitigate global warming to the need to adapt to its current and future impacts.

Numerous methods for the assessment of climate change impacts on agriculture have been proposed (e.g. Banerjee et al. 2014; Calzadilla et al. 2013; Howden et al. 2007; Mendelsohn 2014; Molua 2009; Morton 2007). A vast body of literature has shown that social and economic factors, along with environmental change, contribute negatively to the scale of the impact (e.g. Antwi-Agyei et al. 2012; Harvey et al. 2014; Lindoso et al. 2014; Sommer et al. 2013). Some of these studies (Berry et al. 2006; Harvey et al. 2014; Lindoso et al. 2014; Luers et al. 2003) are framed within the concepts of risk and vulnerability.

The various existing definitions of risk and vulnerability have created a heterogeneous understanding of the terms, leading to disagreement within the scientific community, concerning in particular how to measure imprecisely defined variables (Birkmann 2006b; Füssel 2007; Gain et al. 2012). Nevertheless, there is common understanding that vulnerability is a component of risk and a condition for a system to be adversely affected (IPCC 2014b).

Recent vulnerability assessment frameworks have conceptually integrated the research streams of climate change adaptation (CCA) and disaster risk management (DRM) (Birkmann et al, 2013; Gain et al. 2012; Giupponi et al. 2015; IPCC 2012). The Fifth Assessment Report (AR5) of the Intergovernmental Panel for Climate Change (IPCC) recognizes that "vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC 2014b, p. 5). However, in the AR5 of the IPCC, exposure is considered an external element while assessing risk. Alternatively, Birkmann et al. (2013) suggest that vulnerability is a function of exposure, susceptibility and (lack of) resilience. Of relevance to the agricultural systems analysis under global environmental change is the vulnerability framework proposed by Turner II et al. (2003), which is in line with the CCA stream of thoughts and strongly emphasizes human-environmental linkages.

When referring to vulnerability assessment for agricultural systems, three distinctive research streams are highlighted in the literature:

-The research stream on agro-ecological (AE) assessments (e.g. Liu et al. 2013; Srivastava et al. 2010) considers the sensitivity of crop production to climatic shocks. The methodological approaches of this stream include statistical and multi-criteria analysis of AE indicators;

- The economic assessments of the agricultural sector analyse the effects of climate change on its economic performance (e.g. Calzadilla et al. 2013; Molua 2009). Key performance indicators are agricultural productivity and farm income. The assessments are based primarily on econometric analysis using partial or general equilibrium models.

-The assessments on social aspects (e.g. Antwi-Agyei et al. 2012; Harvey et al. 2008; Morzaria-Luna et al. 2014) present the social vulnerability perspective. This research stream analyses the relationship between agricultural performance and climatic hazards by incorporating indicators of adaptive capacity.

The interactions between AE and socio-economic (SE) aspects within the agricultural systems are complex across spatio-temporal scales. Therefore, holistic vulnerability assessments for agriculture that reflect the multi-dimensional nature of the concept have received less attention (e.g. Balbi et al.

2013; Monterroso et al. 2014; Zarafshani et al. 2012; Yuan et al. 2015). This approach requires: (i) an integrated consideration of cross-disciplinary indicators; and (ii) a suitable normalization or standardization procedure, and aggregation methods (Gain and Giupponi 2015).

In order to reduce vulnerability in a changing world, it is necessary to assess and compare plausible case-specific strategies, including CCA (Balbi et al. 2013; Giupponi et al. 2013). The latter involves decisions and actions, which could mitigate damage or take advantage of new opportunities (IPCC 2014a). The availability of numerous funding mechanisms, including those under the United Nations Framework Convention on Climate Change (UN FCCC), and a range of bilateral and multilateral agreements (Conway and Mustelin 2014; Hulme et al. 2011) have led to the intensification of the international community's commitment to enhancing CCA action. The Copenhagen Accord, adopted at the Fifteenth session of the Conference of the Parties (COP) to the UN FCCC, offered opportunities to significantly advance the climate change agenda and to establish a solid enabling environment for CCA. In the following years, there was a steady increase in the emphasis upon adaptation at the COP to the UN FCCC, in recognition of the crucial role of National Adaptation Plans (NAPs) in building adaptive capacity and resilience of the socio-ecological systems, and reducing their vulnerability to climate change. Effective CCA strategies have been identified as a combination of both bottom-up reactive local actions at state level and global initiatives (Adger et al. 2005; Biesbroek et al. 2010; Ladoba 2014).

Vulnerability approach to adaptation planning is a central concept in key international climate change frameworks and funding mechanisms (Füssel and Klein 2006; IPCC 2014b). Adaptation action in agriculture is influenced by the effects of climatic (climate change, variability and extremes) and non-climatic (economic conditions, politics, environment, society and technology) conditions and forces. Therefore, the vulnerability approach to CCA could be suitable for identifying case-specific conditions under which adaptive decisions should be made (Smit and Skinner 2002).

Vulnerability reduction in the agricultural sector should be approached in a sustainable mode. The IPCC (2014a, p. 26) defines sustainability as "a dynamic process that guarantees the persistence of natural and human systems in an equitable manner". However, this aspect is poorly reflected in the existing vulnerability assessment methods for agriculture.

Looking across disciplines, the most common method for quantification of vulnerability is the indicator-based assessment. Despite the existence of concerns over the actual quantification of vulnerability,

vulnerability assessment tools have a significant positive impact upon scientifically sound and socially coherent adaptation planning (Giupponi et al. 2013). Furthermore, vulnerability indicators appear to be useful tools for communicating complex state-of-affairs (Hinkel 2011).

A better understanding of the factors which make (local, national, global) agricultural systems vulnerable to climate change and hazards would support governments in developing national and global CCA strategies. With this motivation, the objective here is to contribute to the literature on vulnerability assessment for agriculture in the context of CCA by proposing a holistic approach and integrating assessment results with a sustainability analysis of adaptation scenarios. We provide a comprehensive assessment of vulnerability of agricultural systems at a sub-national scale through aggregation of AE and SE information into one agricultural systems vulnerability index (ASVI). We further seek to evaluate the effect of a set of CCA measures on regional vulnerability, while accounting for the sustainability of the AE and SE systems.

The methodological framework is applied to the case study of the Khorezm region of Uzbekistan, which is a proper example of: (i) an irrigated agricultural system in an arid/semi-arid region threatened by significant reduction of (Amu Darya) river water flows during the vegetation period, also caused by global change (Schlüter et al. 2013); (ii) a sub-national vulnerability assessment in a country with an agricultural sector under strong and close surveillance of the national administration, including the provision of state production quotas for cotton and wheat; (iii) a centralized water management system (Veldwisch et al. 2012); and (iv) limited data availability.

2 Methodological framework

2.1 A conceptual model for vulnerability assessment

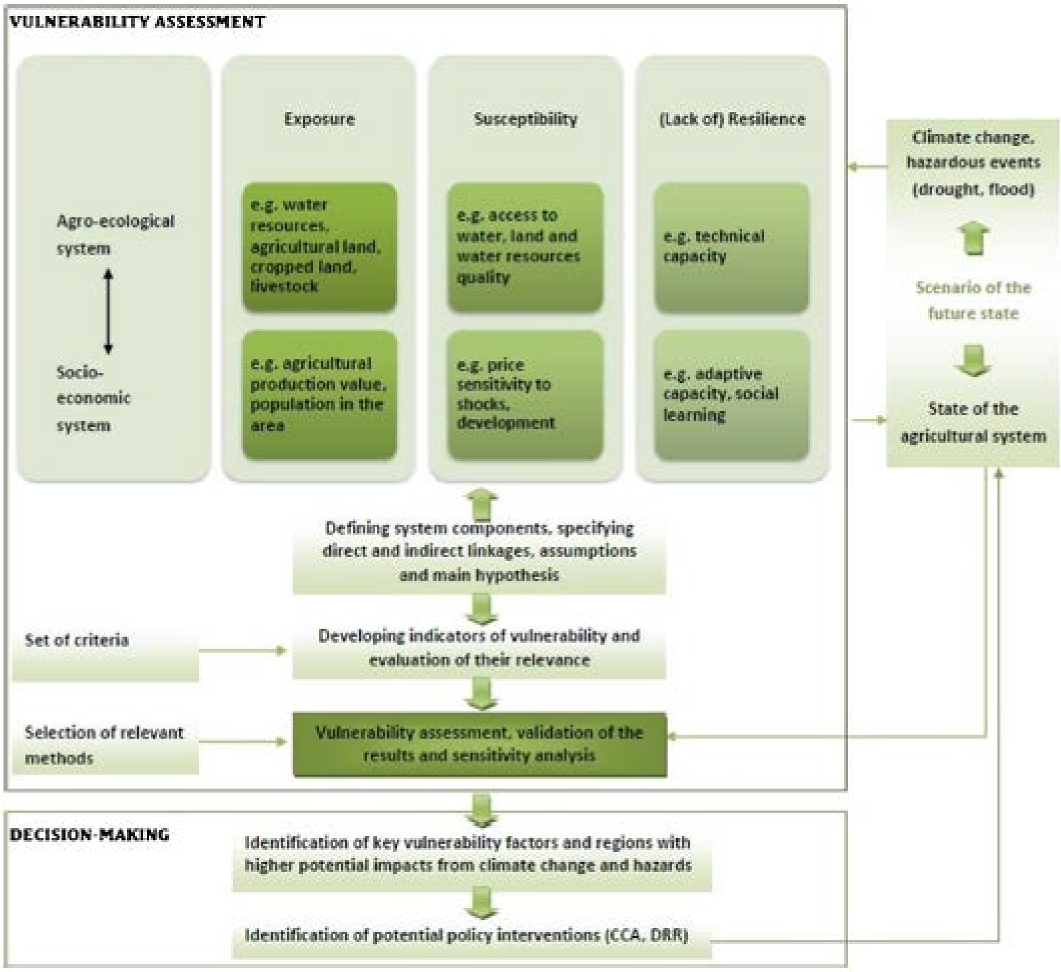
According to Spedding (1988, p. 15), “the operational units of agriculture may be described as agricultural systems, including all the variations in size and complexity of a unit that are called enterprises, farms, plantations, regional and national agricultures”. Here references are made to the regional and national agricultural systems, which consist of cropping/livestock and ecological (i.e. natural resources such as land and water) systems. In a broader context, the regional and national agricultures have agrarian structures combining the economic, social, technical and political factors and processes that affect agricultural production. The agrarian structure therefore describes the socio-economic and technological factors of vulnerability.

To structure this complex analysis, we group the components of the agricultural systems into those with an AE dimension (e.g. soil properties, cropping-patterns, irrigation network) and SE dimension (e.g. economic activities and social relations) (Fig. 1). This approach allows for further analysis of the results in terms of environmental and SE sustainability.

To conceptualize the vulnerability analysis, we draw upon the vulnerability frameworks of Birkmann et al. (2013) and Turner II et al. (2003), and refer to the definitions specified in the glossary of terms of the AR5 of the IPCC (IPCC 2014a) (Fig.1). We examine exposure through indicators, which reflect the presence of AE and SE assets or resources that could be adversely affected by climate change or hazard events. Hazards due to global climate change are considered an external pressure (or shock) with a degree, magnitude and probability of occurrence, without necessarily being in direct contact with the system. Framing the exposure in this way allows us to evaluate climatic scenarios and link the vulnerability assessment to further risk analysis. Similarly, the climate vulnerability index (CVI) (Sullivan and Meigh 2005) and water vulnerability index (WVI) (Sullivan 2011) contain indicators including surface water availability and climate impact on water resources among others.

The factors that determine the susceptibility of the system are the properties predisposing elements at risk to suffer harm (Birkmann et al. 2013). Resilience is related to factors shaping the ability of a system to cope with and adapt to shocks or gradual changes, such as functional efficiency, capacity, diversity, and accessibility.

Operationalizing vulnerability assessment should facilitate decision-making through: (i) an identification of key vulnerability factors and regions with higher potential impacts of climate change and hazards, and (ii) ex-ante evaluation of CCA and risk reduction policies. For this purpose, it is essential to provide an explicit analysis of vulnerability that can be useful for improved planning and decision-making in the agricultural sector. In addition, the development of policy scenarios should be an integral part of the analysis (Fig. 1). The proposed methodological framework (Fig. 1) also suggests that adaptation and risk mitigation efforts increase the resilience and decrease the susceptibility and exposure of the agricultural system. Furthermore, the conceptual model for vulnerability assessment for agricultural systems highlights the importance of achieving balance between the two agricultural sub-systems (AE and SE) through sustainable climate policies.



[Figure 1 (Conceptual model for vulnerability assessment for agricultural systems) here]

2.2 Selection of agro-ecological and socio-economic indicators

Appropriate indicators for vulnerability assessment can be developed in a systematic way by: (i) defining the system boundaries; (ii) understanding the direct and indirect linkages between the system components and outlining the main assumptions and hypotheses; (iii) preparing a preliminary list of indicators based on existing literature on relevant indicators; and lastly, (iv) selecting a final set of indicators based on stakeholders' involvement (Gain et al. 2012). The final list of vulnerability indicators should contain the most sensitive factors related to the agricultural system – climate change nexus.

The available literature is rich in guidance for selection of indicators (e.g. Birkmann 2006; OECD 2008). However, in this paper we have incorporated tangible criteria considering the specific vulnerability assessment context. Firstly, both agricultural systems and vulnerability have a dynamic nature and therefore evaluators should account for slow-changing variables, such as soil-properties (Luers 2005). Specifically, agricultural systems are composed of human and environmental components, both of which change over time but at a different pace. For example, agricultural productivity in a certain region might increase in a relatively shorter period; however, unsustainable resource utilization could lead to land degradation in a longer period. Similarly, the concept of vulnerability implies change over time, not only due to changes in the system components, but also as a result of adaptation responses to climate change (Birkmann et al. 2013). Secondly, given the strong grip of the national administration on the lower level administrations, including those in the case study, the proposed methodological framework refers to multi-level analysis, i.e. national, regional and even sub-regional levels. However, this intention may be restricted by differences in data availability at these levels and make it necessary to re-scale from sub-regional to national assessment, and vice versa. In general, larger sets of statistical data for SE variables are available at national and regional levels, while AE information is accessible mainly at local level. Thirdly, selected indicators should capture the impact of the intended policy scenarios upon the provision of robust information to decision-makers.

2.2.1 Indicators used for the agro-ecological system

The vulnerability of the AE systems is determined by factors of exposure, susceptibility and resilience. Following the definitions provided (Sections 1 and 2) the level of exposure of an AE system could be measured through natural resource indicators such as water availability and cropland. For example, it is assumed that regions with a higher share of cropland are more exposed to climate change and shocks because they have more assets that could be adversely affected. Susceptibility is related to the properties of the AE system, which make the system more fragile and sensitive, grouped here into environmental quality and degradation, and agricultural production sensitivity, respectively. Soil and water quality (including groundwater and irrigation), for example, are among the main environmental compartments in agro-environmental assessments (Giupponi and Carpani 2006). Agricultural production loss is an indirect output measurement of agricultural sector sensitivity to climate pressures.

Resilience is shaped by agricultural diversity, and productivity, technical efficiency and capacity. Diversity is a well-recognized pre-condition for resilience (Schouten et al. 2012). Thus, it is assumed that agricultural production differentiation is correlated to the AE system's greater capacity to cope with changes and shocks. Aspects such as water and land productivity, and irrigation system efficiency and capacity are factors used to reflect the resilience and overall capacity of the production process.

2.2.2 Indicators used for the socio-economic system

Exposure of the SE system is composed of economy (agricultural output) and people. It is assumed therefore that regions with a higher agricultural output or regions with a higher population density will be more exposed to climate effects. The factors that shape the sensitivity of the human component are dependence and development, and access to resources. It is assumed that regions that are highly dependent on the agricultural sector or have a low rate of production growth would be at a high risk of water scarcity (Gain and Giupponi 2015). Furthermore, social vulnerability studies include indicators for access to resources such as access to water for irrigation (e.g. Sullivan and Meigh 2005). Finally, the resilience of the SE system was measured using indicators of SE agrarian structure. The latter characterize the coping and adaptive capacity of the regions, which is limited or enhanced by the system's properties, such as land ownership, farm typology and labour organization.

2.3 Aggregation and policy evaluation method

Normalisation, one of the preliminary steps for the aggregation of diverse indicators, makes it possible to deal with the different measurement units. Several normalization techniques exist in the literature (OECD 2008), and the best choice depends on the indicators under consideration, and the preferences of the decision-maker (Gain and Giupponi 2015). After normalizing the indicator values (i.e. transforming them into real numbers between zero and one), the final outcome (in this paper the ASVI) is the result of a hierarchical combination of several indicators that need to be aggregated. The need to aggregate multi-dimensional information constitutes a challenge for the selection of a methodological approach. Suitable aggregation algorithms need to be selected in accordance with the logic of the conceptual framework, but also according to the elicited preference of the decision makers (Gain and Giupponi 2015; Giupponi et al. 2013). Statistical and participatory methods could be applied for composite indicator development. For instance, large datasets are often aggregated through a combination of multivariate statistical techniques, such as principal component and factor analysis. In addition, there are also widely applied simplified methods such as simple additive weighting (SAW) with equal weights.

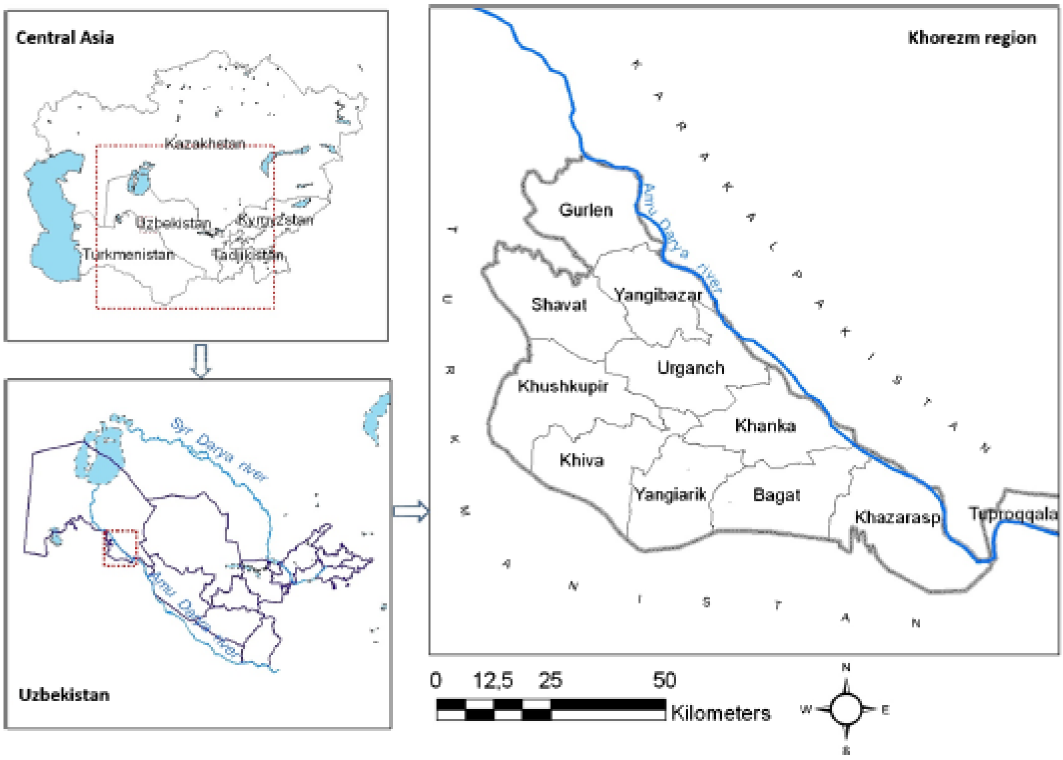
The proposed assessment method provides flexibility in terms of analytical approaches according to the desired outcome. For example, the method can be applied for: participatory or data-driven vulnerability assessment; spatial or aggregated analysis; multi-criteria decision analysis of climate change and policy scenarios. The framework can also integrate the output of external models. We perform the vulnerability assessment using the mDSS decision support tool developed within the NetSyMod framework (Network Analysis – Creative System Modelling – Decision Support) (Giupponi et al. 2008). The mDSS software was initially developed as a Multi-sectoral Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale (Giupponi 2007). The tool has been used in several cases to facilitate the involvement of stakeholders and experts in environmental decision-making (Giupponi 2014). In this study we adopted the mDSS tool for: (i) normalization and aggregation of the spatial data; (ii) ranking within and across scenarios and mapping of the results; and (iii) sensitivity analysis of the obtained ranks of scenario options.

3 Application of vulnerability assessment method to irrigated agriculture in the case study area

3.1 System of agro-ecological and socio-economic indicators for Khorezm

Khorezm is located in the northwest, arid/semi-arid parts of Uzbekistan (60°05′ and 61°39′ E longitude and 41°13′ and 42°02′ N latitude) and comprises 680,000 ha (Fig. 2). The population is 1.7 million, while agriculture accounts for about 35% of the regional gross production. The livelihoods of the majority of the people are highly dependent upon the Amu Darya river waters as the region is characterized by irrigated agriculture. The cropland of Khorezm comprises 270,000 ha and is entirely dependent on irrigation. Small areas of the irrigated land are also used for livestock rearing, horticulture and gardens. Aleksandrova et al. (2014) previously summarized the determinants of regional climate change vulnerability for the study area, to which we refer here and summarise below.

Annual precipitation is barely 100 mm and occurs mainly during the fall and winter seasons, while the annual evapotranspiration is 1400–1600 mm. Climate change threatens the Khorezm region through changes in the quantity and timing of Amu Darya discharges (Schlüter et al. 2013) leading to more frequent drought events.



[Figure 2 (Map of the Khorezm region of Uzbekistan and its administrative districts) here]

Environmental deterioration, including groundwater salinization and land degradation, has become a major concern in Khorezm. The average groundwater salinity value for Khorezm continues to lie in the moderately saline waters (Rhoades et al. 1992), meaning that it does not directly affect the performance of crops. However, increasing groundwater salinity combined with high temperatures driving evapotranspiration have exacerbated secondary soil salinization (Tischbein et al. 2012). Consequently, more water is required to leach the accumulated salts. At present, about 40-60% of the croplands in the region are salinized. The soil organic matter (SOM), estimated at only 7.5.g kg^{-1} on average in the topsoil (Akramkhanov et al. 2012), has been continuously affected by intensive soil tillage, high temperatures and intensive irrigation. In addition, soil degradation has increased significantly, particularly during water-scarce periods.

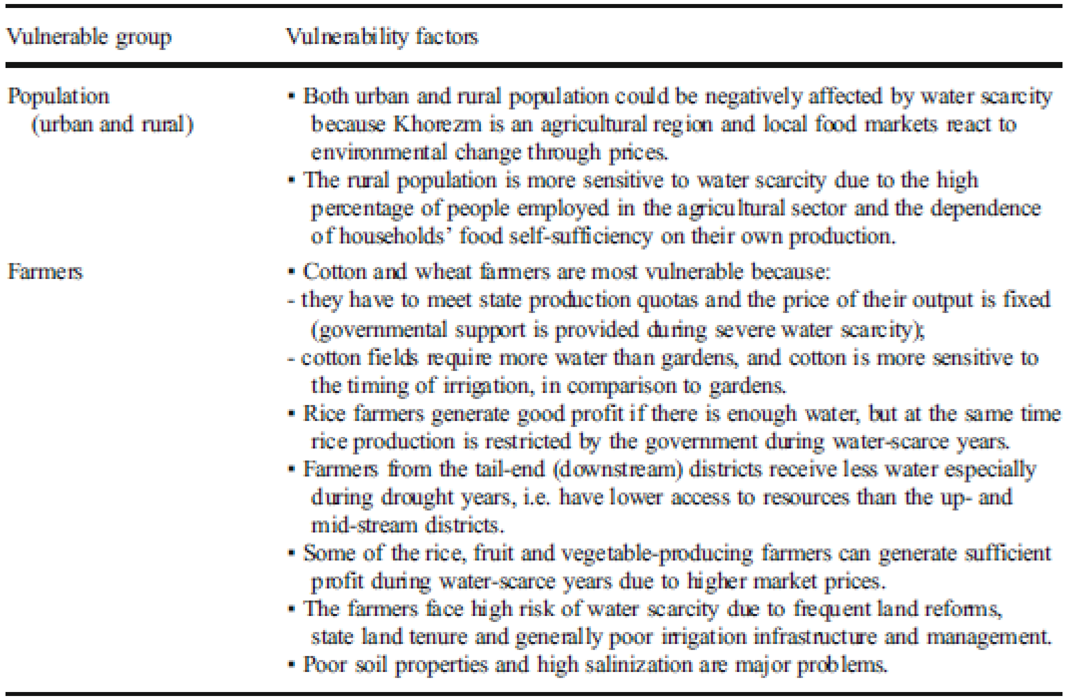
The sensitivity of the agricultural systems in Khorezm is determined by several factors such as: (i) the dominance of high water demanding crops, mainly cotton (*Gossypium hirsutum*) and rice (*Oryza sativa*), and to a lesser extent wheat (*Triticum aestivum*); (ii) the high dependence on irrigated agriculture; and (iii) the low diversification of farmers' income; (iv) the high percentage of the rural population which accounts for 67% of the total population (Aleksandrova et al. 2014).

Local water distribution management is a prime determinant of the access to water of farmers, especially during water-scarce seasons. It includes storage of water in the Tuyamuyun reservoir (upstream from Khorezm) and sub-regional distribution through primary (inter-region), secondary (inter-farm) and tertiary (on-farm) canals. The inefficiency of the irrigation system together with the restrictive water management by the national and regional administration have had a particularly high impact. Existing policies prioritize water distribution to cotton and wheat fields, and restrict rice cultivation in case of expected water scarcity.

Furthermore, national policies affect the resilience in the region through frequent land reforms, state land tenure and production quotas for cotton and wheat (Aleksandrova et al. 2014). Cotton and wheat farming is dominant, whereas the agricultural diversity varies within the districts of Khorezm. Karimov (2012) found that crop diversification is positively related to the higher technical efficiencies of the farmers in Khorezm.

A survey among key informants (Supplement 1) was conducted based on a semi-structured questionnaire to examine the underlying factors of vulnerability for the last 15 years. Specifically, open-ended questions were used to explore the impacts of past experiences of water scarcity and to characterize the determining factors. In addition, a preliminary list of indicators was presented during focus group discussions among national and international scientists with substantial research experience (4 to 10 years) in the Khorezm region. A total of nine researchers participated, with backgrounds in agricultural economics, water management, environmental monitoring, agronomy and afforestation. Building upon the survey findings (Table 1), focus group recommendations and previous research results (Aleksandrova et al. 2014), the proposed vulnerability assessment method for agricultural systems was operationalized upon data availability. The final set of selected indicators is listed in Table 2 (details are provided in Supplement 2).

[Table 1 (Key vulnerable groups and factors identified by key informants) here]



Vulnerable group	Vulnerability factors
Population (urban and rural)	• Both urban and rural population could be negatively affected by water scarcity because Khorezm is an agricultural region and local food markets react to environmental change through prices. • The rural population is more sensitive to water scarcity due to the high percentage of people employed in the agricultural sector and the dependence of households' food self-sufficiency on their own production.
Farmers	• Cotton and wheat farmers are most vulnerable because: - they have to meet state production quotas and the price of their output is fixed (governmental support is provided during severe water scarcity); - cotton fields require more water than gardens, and cotton is more sensitive to the timing of irrigation, in comparison to gardens. • Rice farmers generate good profit if there is enough water, but at the same time rice production is restricted by the government during water-scarce years. • Farmers from the tail-end (downstream) districts receive less water especially during drought years, i.e. have lower access to resources than the up- and mid-stream districts. • Some of the rice, fruit and vegetable-producing farmers can generate sufficient profit during water-scarce years due to higher market prices. • The farmers face high risk of water scarcity due to frequent land reforms, state land tenure and generally poor irrigation infrastructure and management. • Poor soil properties and high salinization are major problems.

3.2 Scenario specification

3.2.1 Impact of climate change on water flow for irrigation

The latest assessment of the impact of climate change on the water flow to the midstream Kerki gauging station (upstream from the Tuyamuyun reservoir which discharges water to Khorezm), suggests that the average multi-year seasonal discharge will drop by 13% in 2030 and by 22% in 2050 (Schlüter et al. 2013). These findings are based on various assumptions relating to greenhouse gas concentrations, and future institutional and technical conditions. Here, we consider the case of a 20% reduction of the average water flow to each district of Khorezm during the vegetation season (April-September). Even though the expected climate changes and land degradation in the Central Asian region are significant (IPCC 2014b; Mannig et al. 2013), to simplify our feasibility study, we explore the case of reduced water flow in the current environmental conditions.

[Table 2 (Components of vulnerability and selected indicators) here]

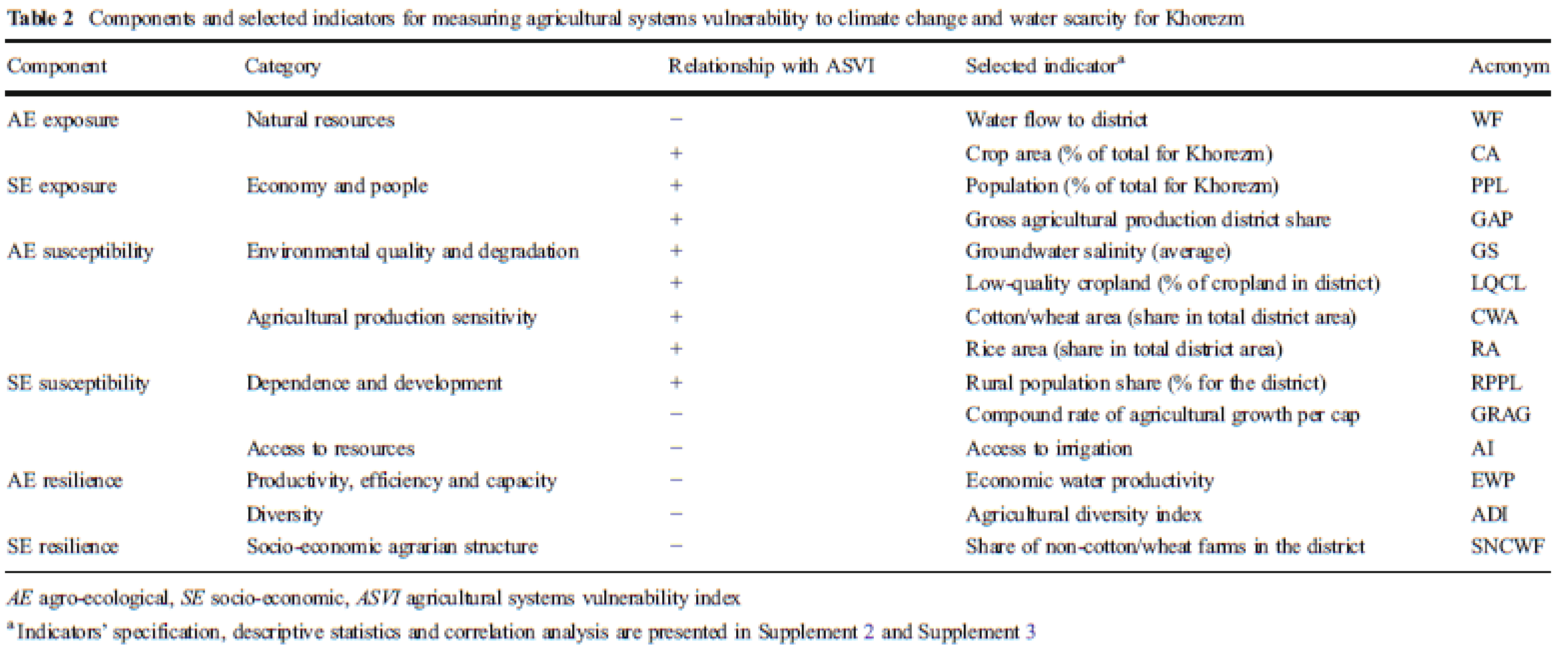


Table 2 Components and selected indicators for measuring agricultural systems vulnerability to climate change and water scarcity for Khorezm

Component	Category	Relationship with ASVI	Selected indicator[a]	Acronym
AE exposure	Natural resources	−	Water flow to district	WF
		+	Crop area (% of total for Khorezm)	CA
SE exposure	Economy and people	+	Population (% of total for Khorezm)	PPL
		+	Gross agricultural production district share	GAP
AE susceptibility	Environmental quality and degradation	+	Groundwater salinity (average)	GS
		+	Low-quality cropland (% of cropland in district)	LQCL
	Agricultural production sensitivity	+	Cotton/wheat area (share in total district area)	CWA
		+	Rice area (share in total district area)	RA
SE susceptibility	Dependence and development	+	Rural population share (% for the district)	RPPL
		−	Compound rate of agricultural growth per cap	GRAG
	Access to resources	−	Access to irrigation	AI
AE resilience	Productivity, efficiency and capacity	−	Economic water productivity	EWP
	Diversity	−	Agricultural diversity index	ADI
SE resilience	Socio-economic agrarian structure	−	Share of non-cotton/wheat farms in the district	SNCWF

AE agro-ecological, *SE* socio-economic, *ASVI* agricultural systems vulnerability index

[a] Indicators' specification, descriptive statistics and correlation analysis are presented in Supplement 2 and Supplement 3

3.2.2 Adaptation policy scenario

According to the available statistical data, the environmental pressures are higher in three districts of Khorezm located at the tail-end of the primary irrigation canals, namely Kushkupir, Shavat and Yangiarik (Fig.2). More specifically, these districts share the following characteristics: the lowest access to irrigation; the lowest cotton yield (Ruecker et al. 2012); high share of low quality cropland; the highest groundwater salinity. Therefore, the following adaptation scenario was explored for those districts:

- 50% reduction in the use of low quality cropland (defined in Supplement 2) for cotton production as a water-saving measure. The existing estimates suggest that eliminating marginal areas (soils with low productivity) from the irrigation plan could save 15-20% surface water (Awan et al. 2012). Therefore, it was assumed that with a 50% reduction in the use of low quality cropland, each of the three districts could save about 10% water;
- 20% reduction of the cotton area in addition to the reduced low quality cropland;
- 100% reduction of the rice areas, which could save up to 1% water (Awan et al. 2012);
- replacement of the reduced cotton area with fruit and vegetable cultivation. This could save about 9% water (Awan et al. 2012) and increase the farmers' income (Bobojonov et al. 2012).

This set of adaptation measures could bring several additional SE benefits. For example, a recent analysis on the prospects of afforestation of the Khorezm's marginal croplands reveals that tree plantations represent an applicable option for income diversification, soil salinity improvement and a decrease in the regional water demand (Khamzina et al. 2012). Furthermore, an overall reduction of the cotton cropland in the range of 17-69% (i.e. reduction of raw cotton production) could maintain the same level of cotton export revenues provided the potential of the cotton value chain were better-exploited, e.g. through investments in the processing sector such as cotton fibre and fabric production for export (Rudenko et al. 2013; Rudenko et al. 2012).

Building upon these findings, it was assumed that adaptation would not have a negative effect upon the indicators for gross agricultural production (GAP) and compound rate of agricultural growth per cap (CRAG) and therefore those elements were kept at the baseline state. However, the agricultural diversity index (ADI) and share of non-cotton/wheat farms (SNCWF) values were increased in accordance with the adaptation scenario, referring to increased resilience and capacity. Moreover, economic water productivity (EWP) should increase, whereas we again assume constant GAP yet less water demand due to the set of measures.

The adaptation scenario developed seeks to explore adaptation options at a sub-regional scale in Khorezm. Imposing water-saving measures only in those districts with the highest environmental degradation and the lowest access to irrigation is a more feasible near-future scenario. Given the governmental policies of prioritization of raw cotton production, the explored set of measures could hardly be introduced across all districts. Furthermore, the proposed adaptation scenario is used for sensitivity tests of the spatial multi-criteria analysis.

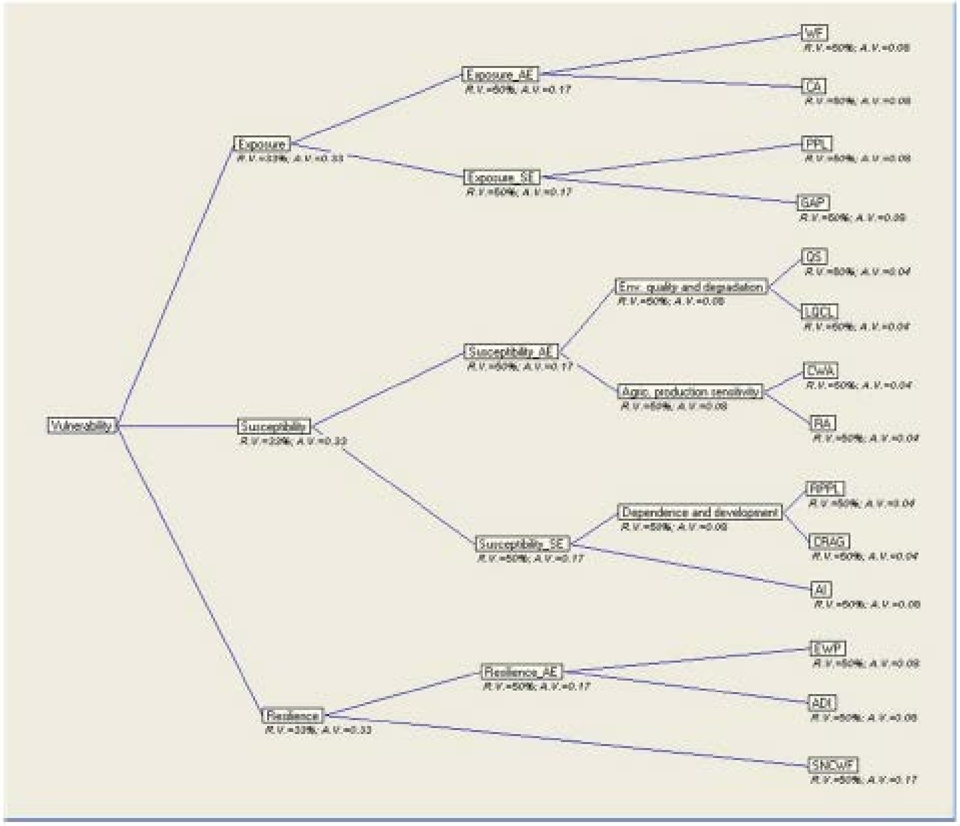
Developing upon the above specifications, two scenarios were explored in this study: (i) 20% reduced water flow under business-as-usual conditions, referred to as BAU -20%; and (ii) 20% reduced water flow with imposed adaptation measures in three districts (as described above), referred to as ADAPT -20%.

3.3 Vulnerability assessment

3.3.1 ASVI computation and results

Descriptive statistics are derived to explore the baseline dataset (Supplement 2). The original data (10 observations) is composed of 14 indicators with diverse measurement units. All variables are quantitative, except access to irrigation (AI), which is categorical. Given this structure of the dataset, Pearson correlation analysis was performed to verify the relationships between the indicators (Supplement 3). The sign of the correlation coefficient r is consistent with the theoretical knowledge, with the exception of some cases (such as r of AI and CRAG), in which r is very low and not statistically significant. Given the small sample size, variables with $r>0.8$ were considered with caution during the robustness tests of the baseline results. High correlation (i.e. $r>0.8$) exists between: GAP and population (PPL); GAP and rural population (RPPL); cotton/wheat area (CWA) and ADI. However, these indicators belong to different sub-components of the ASVI (except GAP and PPL), and were therefore preserved during the first run of the model.

The full dataset, containing baseline data and two scenario matrices (BAU -20% and ADAPT -20%) (i.e. 30 observations and 14 indicators), was normalized (min-max method) and aggregated with mDSS software using SAW. We assigned equal hierarchical weights (EHW). The ranking algorithm was based on the surface area of each district. The hierarchical design allowed us to group the indicators into sub-indices that share the same dimension of vulnerability (Fig. 3). The index values were divided into 3 classes (1-low, 2-medium and 3- high vulnerability) within the range of the minimum and maximum scores: (i) for the baseline scenario; and (ii) jointly for the BAU -20% and ADAPT -20% to provide a basis for adaptation policy evaluation. In the baseline assessment, the ASVI values were in the range 0.45-0.65, while for the two water scarcity scenarios (BAU -20% and ADAPT -20%) the scores ranged between 0.30-0.68.



[Figure 3 (Structure of the agricultural systems vulnerability index (ASVI) for Khorezm) here]

The summary of the results obtained in mDSS, including the level of vulnerability and the associated dominant factors, are provided in Fig. 4 and 5 (detailed description of the vulnerability patterns for each district is provided in Supplement 4). The most critical elements shaping vulnerability within the region differ across the districts. The indicators related to cotton and wheat farming are set into the sensitivity and resilience sub-indices, and the districts with the lowest share of their production fall in the low and medium vulnerability classes. The state of the natural resources (soil, water) and water productivity are also major determinants of the districts' vulnerability to climate pressures. In addition, the population size, rural-urban ratio and gross agricultural output within the region, supplement the spatial variability of the ASVI and its sub-components.

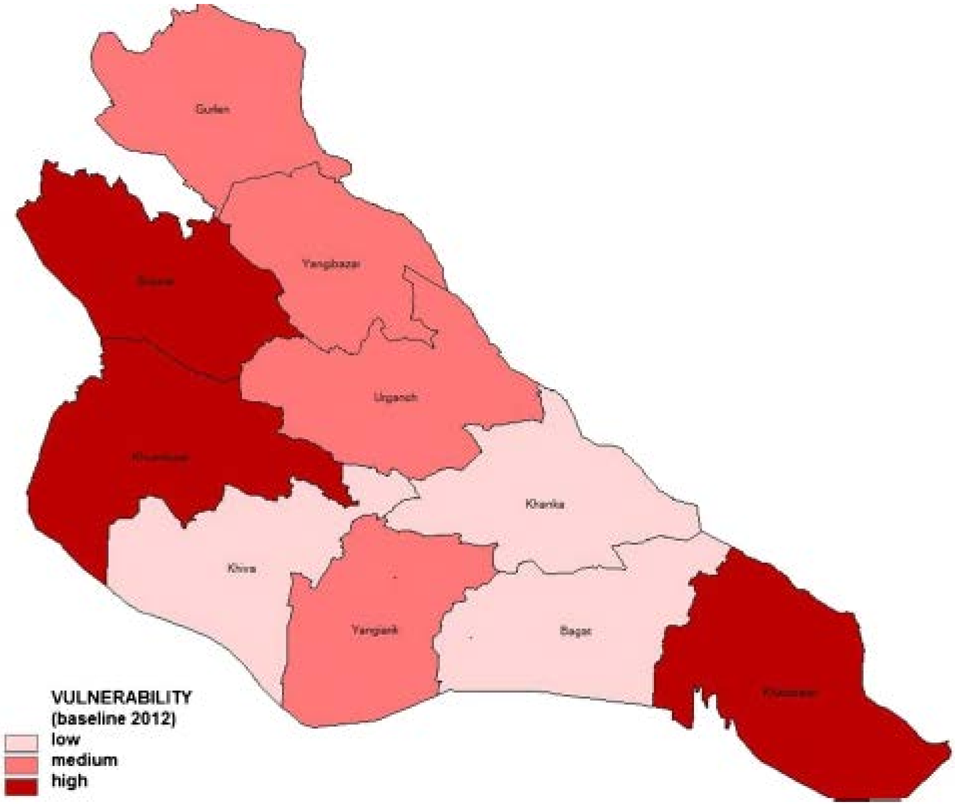


Fig. 4 Spatial distribution of agricultural systems vulnerability index (ASVI) for Khorezm under baseline scenario (2012). The ASVI values for each class are in following range: low 0.45–0.51, medium 0.52–0.58, high 0.59–0.65

[Figure 4 (Baseline index mapping) here]

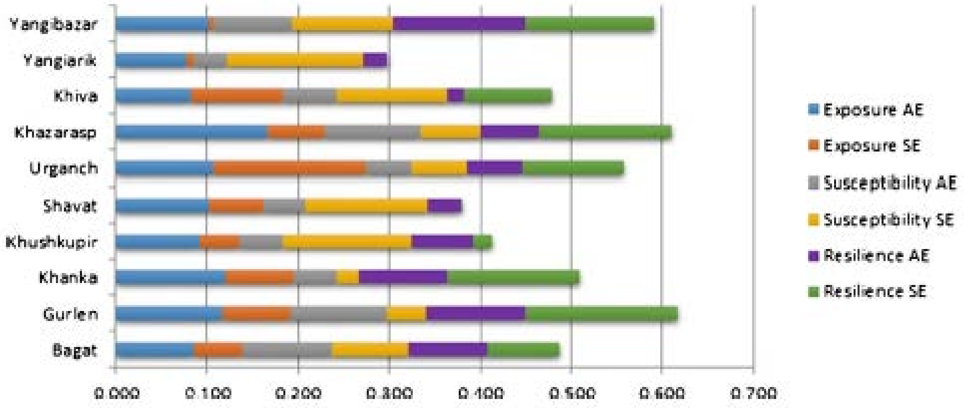


Fig. 5 Distribution of sub-component scores of agricultural systems vulnerability index (ASVI) for Khorezm under baseline scenario (2012) by district. *AE* refers to agro-ecological; *SE* refers to socio-economic

[Figure 5 (Baseline sub-index chart) here]

3.3.2 Sensitivity analysis of the baseline ASVI

Following the baseline estimations, the robustness of the ASVI was carried out by analysing its correlation with the input parameters. Four indicators were significantly correlated (with r>0.6): crop area (CA), CWA, ADI, SNCWF. Given this result and the high correlation between the GAP and PPL indicators belonging to the same sub-component of the ASVI, several sensitivity tests of the weighting method were performed (Table 3).

First, the weight of the indicator PPL was reduced in favour of that of the GAP indicator, since it has very high values in Urgench and Khiva - two urban-dominated districts. However, the effect of the change in the vulnerability class is reflected only in the rank of Gurlen, which has the second highest GAP in Khorezm after Urgench. In addition, the weights of the CA, ADI and SNCWF indicators were reduced separately and jointly, since those indicators showed a higher correlation with the ASVI compared to the rest of the indicators. Change in the vulnerability class occurred solely for Urgench. The last run of the robustness test accounted for the change in the weights of the vulnerability sub-components (exposure, susceptibility, lack of resilience). The latter addressed the correlation problem within the exposure component, and between exposure, lack of resilience and ASVI by assigning lower weights. Those modifications changed the classes of the three districts with the highest exposure indices of all. Lastly, lowering the weight of the SNCWF indicator significantly changed the class of Urgench to one with much higher vulnerability. Given that the class sensitivity under the alternative weighting scheme affects primary Urgench district, we used the EHW approach throughout the analysis.

[Table 3 (Sensitivity of the class agricultural systems vulnerability index (ASVI) due to a change in the assigned weights) here]

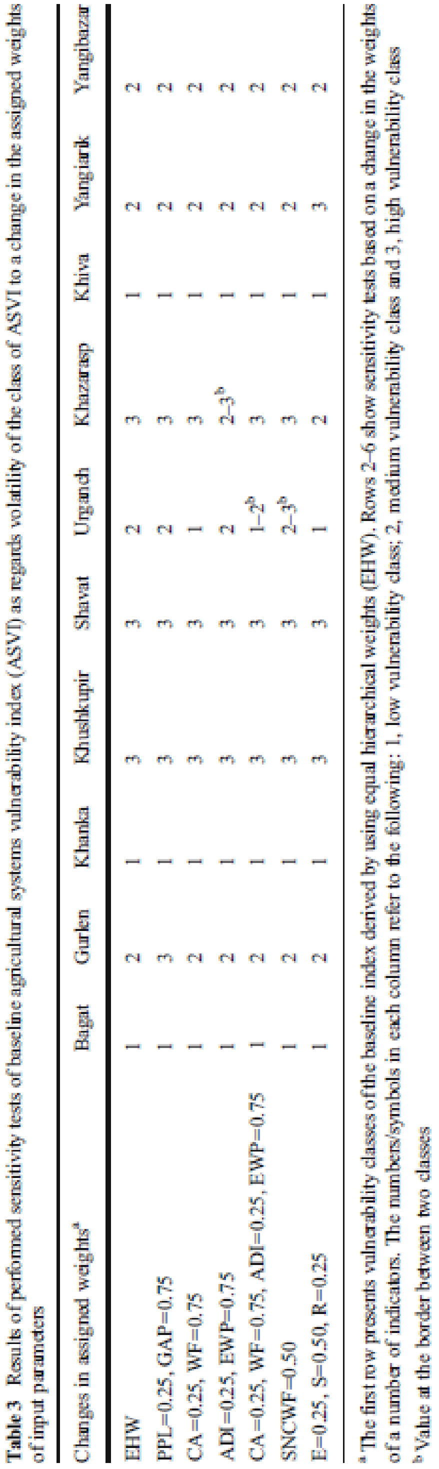


Table 3 Results of performed sensitivity tests of baseline agricultural systems vulnerability index (ASVI) as regards volatility of the class of ASVI to a change in the assigned weights of input parameters

Changes in assigned weights[a]	Bagat	Gurlen	Khanka	Khushkupir	Shavat	Urgench	Khazarasp	Khiva	Yangiarik	Yangibazar
EHW	1	2	1	3	3	2	3	1	2	2
PPL=0.25, GAP=0.75	1	3	1	3	3	2	3	1	2	2
CA=0.25, WF=0.75	1	2	1	3	3	1	3	1	2	2
ADI=0.25, EWP=0.75	1	2	1	3	3	2	2–3[b]	1	2	2
CA=0.25, WF=0.75, ADI=0.25, EWP=0.75	1	2	1	3	3	1–2[b]	3	1	2	2
SNCWF=0.50	1	2	1	3	3	2–3[b]	3	1	2	2
E=0.25, S=0.50, R=0.25	1	2	1	3	3	1	2	1	3	2

[a] The first row presents vulnerability classes of the baseline index derived by using equal hierarchical weights (EHW). Rows 2–6 show sensitivity tests based on a change in the weights of a number of indicators. The numbers/symbols in each column refer to the following: 1, low vulnerability class; 2, medium vulnerability class and 3, high vulnerability class

[b] Value at the border between two classes

3.3.3 Spatial analysis of the ASVI under different scenarios

The change in the aggregated ASVI values under the explored scenarios is given in Table 4. The results show that the lowest vulnerability values are obtained under the scenario ADAPT -20% (values range 0.30 – 0.61), while the highest vulnerability is observed under the scenario BAU -20% (values range 0.47 – 0.68). Changing only one indicator equally across all districts, i.e. water flow (WF) under scenario BAU -20%, leads to a higher overall vulnerability but preserves the original rank order.

The spatial sensitivity of the ASVI to a change in several indicators related to adaptation is high. This is confirmed by the change of the classes of the districts in which the adaptation was imposed (Yangiarik, Kushkupir, Shavat) (Fig. 6). According to the sensitivity analysis performed through mDSS, the most critical criterion[1] for rank volatility for the three districts is the AE exposure sub-component. The most vulnerable districts identified in the baseline assessment (Shavat and Kushkupir) are those with the highest volatility of the classes. However, the rank order of the rest of the districts follows the same pattern.

[Table 4 (agricultural systems vulnerability index (ASVI) values under different scenarios) here]

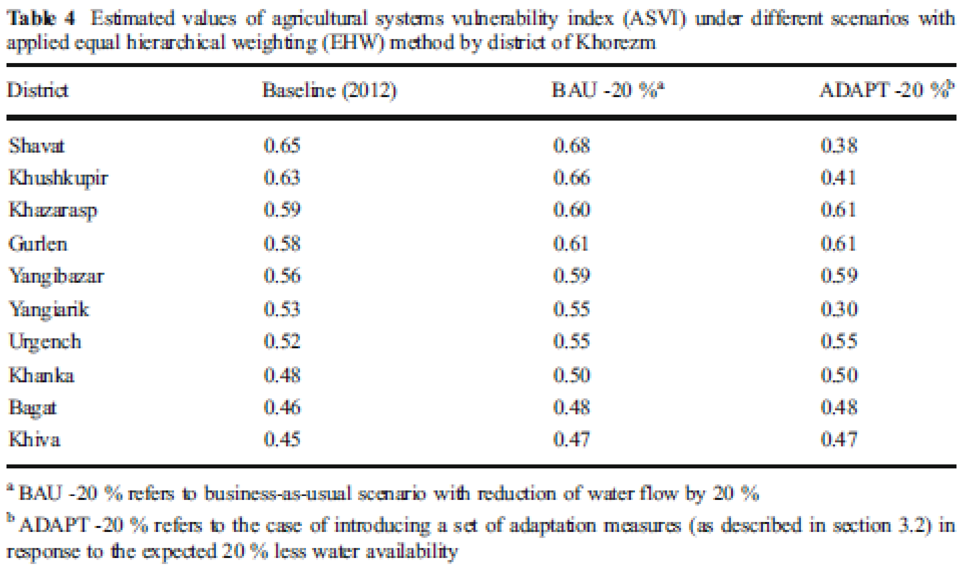


Table 4 Estimated values of agricultural systems vulnerability index (ASVI) under different scenarios with applied equal hierarchical weighting (EHW) method by district of Khorezm

District	Baseline (2012)	BAU -20 %[a]	ADAPT -20 %[b]
Shavat	0.65	0.68	0.38
Khushkupir	0.63	0.66	0.41
Khazarasp	0.59	0.60	0.61
Gurlen	0.58	0.61	0.61
Yangibazar	0.56	0.59	0.59
Yangiarik	0.53	0.55	0.30
Urgench	0.52	0.55	0.55
Khanka	0.48	0.50	0.50
Bagat	0.46	0.48	0.48
Khiva	0.45	0.47	0.47

[a] BAU -20 % refers to business-as-usual scenario with reduction of water flow by 20 %

[b] ADAPT -20 % refers to the case of introducing a set of adaptation measures (as described in section 3.2) in response to the expected 20 % less water availability

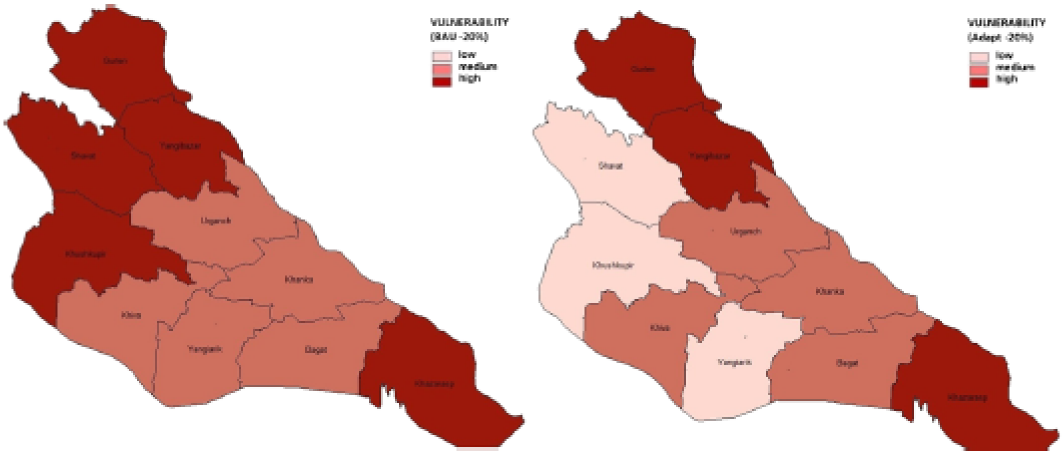


Fig. 6 Agricultural systems vulnerability index (ASVI) for Khorezm under two scenarios—BAU -20 % (business-as-usual scenario with reduction of water flow by 20 %) (*left*) and ADAPT -20 % (adaptation scenario under 20 % less water availability) (*right*). The ASVI values for each class are in the following range: low 0.30–0.42, medium 0.43–0.56, high 0.57–0.68

[Figure 6 (agricultural systems vulnerability index (ASVI) for Khorezm under different scenarios) here]

3.3.4 Adaptation policy evaluation

The analysis presented above demonstrated how local actors can apply the proposed method not only to assess the current vulnerability in Khorezm, but also to explore the effects of plausible scenarios on the spatial distribution of vulnerability. However, to support development planning, we seek to also analyse the effect of adaptation on the AE and SE systems as a means to integrating adaptation policies evaluation with sustainability analysis. For this purpose, we use the vulnerability sub-indices (exposure AE and SE, susceptibility AE and SE, lack of resilience AE and SE) for the three districts in which adaptation measures were imposed (Fig. 7). A change in the values of the sub-indices under the explored scenarios occurs only in four components, namely, exposure AE, susceptibility AE, lack of resilience AE and SE.

The sustainability patterns for Kushkupir and Shavat are similar since the two districts share common vulnerabilities. Significant reduction of AE susceptibility and overall lack of resilience is observed in all districts. The increased SE resilience, determined by the indicator for the type of farming, has a very strong influence on the overall vulnerability reduction.

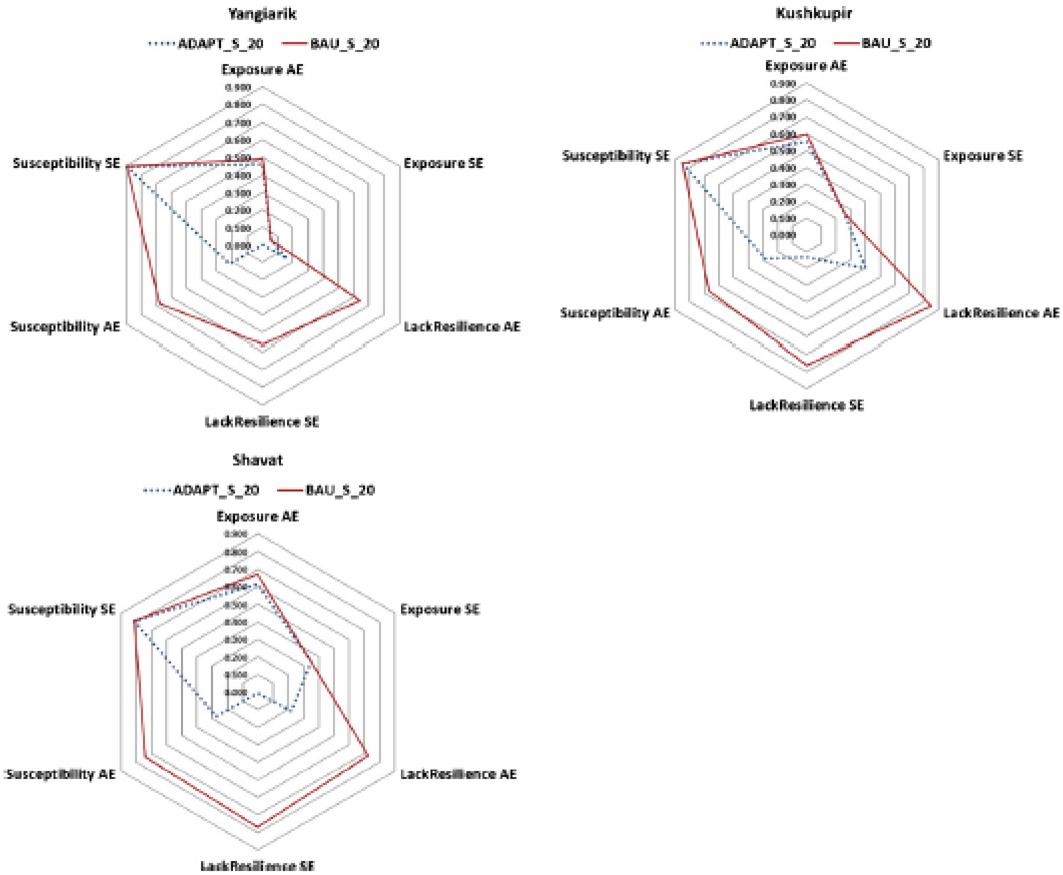


Fig. 7 Comparison of sub-component scores of the agricultural systems vulnerability index (ASVI) for three districts of Khorezm under two scenarios—BAU_S_20 % (business-as-usual scenario with reduction of water flow by 20 %) and ADAPT_S_20 % (the case of introducing a set of adaptation measures in response to expected 20 % less water availability). *AE* refers to agro-ecological; *SE* refers to socio-economic

[Figure 7 (Comparison of the sub-component scores of the agricultural systems vulnerability index (ASVI) for three districts of Khorezm under different scenarios) here]

4 Discussion

Global change and water availability, in particular, are of major concern in achieving food security and enhancing rural development in Central Asia. Djanibekov et al. (2013a) assessed that the pressure on the water resources in Uzbekistan is expected to rise significantly due to increasing economic growth, unless policy actions take place. Looking into these pressing needs, the vulnerability assessment for Khorezm could serve as a model for the analyses of policy implications at sub-national level. While previous research in the case study region looked into the benefits of options for improved land and water management (e.g. Djanibekov et al. 2013b; Martius et al. 2012; Rudenko et al. 2013), a multi-dimensional assessment of the regional vulnerability to climate change at sub-national level was performed here, linking multiple dynamic factors and policy responses into aggregated information for policy-makers.

This study found that there are significant spatial differences between the AE and SE determinants of the districts' vulnerability, which should be considered in the rural development and climate change policies. The explored adaptation scenario targeted the districts with the poorest agro-environmental conditions. A differential approach to adaptation planning which considers the spatial differences could be a feasible pathway to initiate adaptation, given constraints in the region such as state production quotas and the need for substantial investments in the irrigation infrastructure (Aleksandrova et al. 2014), while contributing to a more equal development. Bekchanov et al. (2010) already discussed the importance of equal water distribution in improving low water productivity in the tail-end districts. Similarly, Dubovyk et al. (2012) recommend prioritized mitigation planning in the low-fertility lands located close to the natural sandy desert, since land degradation in those areas is significantly high. As mentioned, tree plantation is a suitable risk mitigation, water saving and income diversification policy (Section 3.2). Importantly, the districts with the highest environmental susceptibility have a high share of land for cotton cultivation. Therefore, agricultural production diversification is crucial for regional resilience, especially in the most vulnerable districts.

The vulnerability analysis for Khorezm could be further extended to risk assessment, considering future environmental and SE change. The case study presented is an example of data constrained vulnerability assessment. Therefore the analysis would benefit from the involvement of key stakeholders in the ASVI and scenario development process. Adaptation policy impact assessments from external models could be linked to the framework through the mDSS tool for multi-criteria analysis of various policy options.

The vulnerability assessment for the agricultural sector requires an integrated approach coupling AE and SE systems. This concept should also relate to dynamic processes before becoming suitable for scenario analysis. The proposed approach bridges the vulnerability assessment with policy decision-making, which makes it a useful supplementary methodology for identifying hazard prevention policies and CCA measures.

The ASVI tool allows integrated, spatial and comparative assessment of local vulnerability to climate change and hazards. Furthermore, the method presented here adds several features to the vulnerability assessment methods for agricultural systems that are not common in the current literature. Firstly, the ASVI incorporates indicators reflecting global change (such as land degradation) impacts at a regional scale, which makes it compatible with further risk analysis. Secondly, the proposed method is suitable for evaluation of adaptation scenarios considering three pillars of sustainability (environment, society, economy), and hence the ASVI tool incorporates the core principles of the global agenda for sustainable development under climate change. In addition, the tool could facilitate discussion among local stakeholders for identification of priority regions and areas for policy intervention. Therefore, policy-makers working in the field of agriculture can adopt the framework in order to identify sustainable solutions of local issues under climate change.

The methodology is transferable to other case studies, providing flexibility in terms of weighting and aggregation methods. We explored non-participatory techniques, but the selected mDSS software is a proven tool for policy evaluation with stakeholders' involvement (Giupponi 2007 2014; Giupponi et al. 2008). While further work is required to refine the methodology for wider applicability, the approach proposed here could facilitate dialogues among local and national actors.

The analysis performed aimed at exploring the applicability of the method in assessing the impact of the potential reduction of irrigation water availability and of the set of adaptation measures upon the Khorezm regional vulnerability. The application in the case study considers min-max linear scaling for normalization, which is a commonly used method in hierarchical models. The hierarchical approach to the configuration of social vulnerability indices is highly accurate though a certain level of uncertainty originates at the weighting stage (Tate 2012). Special attention was paid, therefore, to the weighting algorithm of the case study assessment. The robustness tests through a change in the weights of the baseline ASVI showed that the index is highly sensitive to the AE exposure and resilience indicators. However, the vulnerability class of only one district reflected these changes, which is most likely related to the highest values of several exposure indicators for the district. The sensitivity tests showed satisfactory stability of the ranks under different scenarios.

This study has several other acknowledged shortcomings. First, the method has only been exemplified through the Khorezm case study. Even though indicator development involved local stakeholders, a backward communication of the final results to the key policy-decision makers was not feasible.

Second, the adaptation scenario developed is based on literature review findings. Therefore, it is limited by the assumed changes in, or preserved constant values of, the AE and SE parameters. For instance, climate change would affect crop production through a change in the seasonal agro-meteorological conditions not only through the irrigation water availability. Nevertheless, the incentive behind the scenario analysis was to demonstrate the applicability of the vulnerability assessment approach for policy evaluation, and to explore the uncertainty in the use of the developed ASVI.

Third, we have concentrated on a district scale analysis within a region. Spatial up-scaling of the vulnerability approach, however, is associated with several challenges, such as: (i) possible loss of information during the process of transferring the approach from a local to a higher level; and (ii) assumptions suitable for one spatial level might not be adequate for another level (Eriksen and Kelly 2007; Fekete et al. 2010). In addition, the choice of scale yields different relationships between the indicators (Tate 2012).

5. Conclusion

Arid and semi-arid regions occupy vast territories in Africa, South and Central Asia. The decreasing water availability in major rivers predicted for many of these regions means that nations and communities need to adapt to these environmental changes (IPCC 2014b). The international community has already recognized that effective CCA strategies should be built upon local and regional knowledge of vulnerability and sustainable practices (e.g. IPCC 2014b, IPCC 2012). However, adaptation strategies based only on local and community level adaptation are frequently inadequate in accounting for interactions with regional and global drivers. Therefore, more robust multi-scale initiatives are required (Laboda 2014) to obtain significant impacts on large proportions of affected population. Furthermore, the AR5 of the IPCC postulates that adaptation should be developed by integrating strategies targeted at ensuring water availability and supply, food security, and increased agricultural income (IPCC 2014b).

Looking into these emerging issues, this study argues that a holistic approach to vulnerability assessment for agricultural systems could contribute to improved decision-making in CCA at sub-national level, and hence to supporting global efforts intended to build resilient agricultural systems. The study further demonstrates how policy-makers could evaluate the sustainability of adaptation options within the framework of vulnerability.

The proposed assessment method can be used in other geographical areas as a generalized operational method for the aggregation of multi-dimensional spatial information, relevant to describing determinants of vulnerability and upon which scenarios of future conditions could be applied. Hence, the derived ASVI could be a useful tool for: (i) informing adaptation planning in agriculture (e.g. targeted resource allocation), provided that the adequate indicators are considered in each specific case; (ii) facilitating discussion on sustainable local action in response to global change; and (iii) monitoring and evaluation of climate risk management policies. However, we must bear in mind that vulnerability indicators reduce complexity, which could lead to misinterpretation of information, meaning that they should be considered as entry-points for adaptation planning and allocation of resources, rather than as prime criteria (Hinkel 2011).

This study also provides a concrete example of a set of adaptation measures, which are likely to have the potential to be implemented in many irrigated dry regions in Asia and elsewhere. Key strategies supporting global efforts to combat water scarcity in semi-arid regions, as well as environmental deterioration such as soil salinization, that are also suitable for irrigated agriculture include: (i) improved water management; (ii) increased diversification of the agricultural production with reduction of water-intensive crops; and (iii) an applied differential approach to adaptation planning in the sector accounting for environmental and socio-economic vulnerabilities of the agricultural systems.

Notes

[1] The most critical criterion is part of the sensitivity analysis performed in mDSS software. It shows the criterion that could reverse the ranking of the options given the smallest change in its weight

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ZEF/ UNESCO Project Database

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Table 1 Summary of the results of survey exploring vulnerability to water scarcity in the Khorezm region of Uzbekistan - key vulnerable groups and factors identified by key informants[a]

Vulnerable group	**Vulnerability factors**
Population (urban and rural)	▪ Both urban and rural population could be negatively affected by water scarcity, because Khorezm is an agricultural region, and local food markets react to environmental change through prices. ▪ The rural population is more sensitive to water scarcity due to the high percentage of people employed in the agricultural sector and the dependence of households' food self-sufficiency on their own production.
Farmers	▪ Cotton and wheat farmers are most vulnerable because: - they have to meet state production quotas and the price of their output is fixed (governmental support is provided during severe water scarcity); - cotton fields require more water than gardens, and cotton is more sensitive to the timing of irrigation, in comparison to gardens; ▪ Rice farmers generate good profit if there is enough water, but at the same time rice production is restricted by the government during water scarce years. ▪ Farmers from the tail-end (downstream) districts receive less water especially during drought years, i.e. have lower access to resources than the up- and mid-stream districts. ▪ Some of the rice, fruit and vegetable-producing farmers can generate sufficient profit during water scarce years due to higher market prices. ▪ The farmers face high risk of water scarcity due to frequent land reforms, state land tenure and generally poor irrigation infrastructure and management. ▪ Poor soil properties and high salinization are major problems.

[a]The list of key informants included in the survey is provided in Supplement 1. The survey was conducted in April and May 2013 in the Khorezm region of Uzbekistan by the lead author. A total of 10 unique interviews with key informants were performed

Table 2 Components and selected indicators for measuring agricultural systems vulnerability to climate change and water scarcity for Khorezm

Component[a]	**Category**	**Relationship with ASVI**[b]	**Selected indicator**[c]	**Acronym**
AE exposure	Natural resources	-	water flow to district	WF
		+	crop area (% of total for Khorezm)	CA
SE exposure	Economy and people	+	population (% of total for Khorezm)	PPL
		+	gross agricultural production district share	GAP
AE susceptibility	Environmental quality and degradation	+	groundwater salinity (average)	GS
		+	low quality cropland (% of cropland in district)	LQCL
	Agricultural production sensitivity	+	cotton/wheat area (share in total district area)	CWA
		+	rice area (share in total district area)	RA
SE susceptibility	Dependence and development	+	rural population share (% for the district)	RPPL
		-	compound rate of agricultural growth per cap	GRAG
	Access to resources	-	access to irrigation	AI
AE resilience	Productivity, efficiency and capacity	-	economic water productivity	EWP
	Diversity	-	agricultural diversity index	ADI
SE resilience	Socio-economic agrarian structure	-	share of non-cotton/wheat farms in the district	SNCWF

[a] AE refers to agro-ecological; SE refers to socio-economic

[b] ASVI refers to agricultural systems vulnerability index

[c] Indicators specification, descriptive statistics and correlation analysis are presented in Supplement 2 and Supplement 3

Table 3 Results of performed sensitivity tests of baseline agricultural systems vulnerability index (ASVI) as regards volatility of the class of ASVI to a change in the assigned weights of input parameters

Changes in assigned weights[a]	**Bagat**	**Gurlen**	**Khanka**	**Khushkupir**	**Shavat**	**Urganch**	**Khazarasp**	**Khiva**	**Yangiarik**	**Yangibazar**
EHW	1	2	1	3	3	2	3	1	2	2
PPL=0.25, GAP=0.75	1	3	1	3	3	2	3	1	2	2
CA=0.25, WF=0.75	1	2	1	3	3	1	3	1	2	2
ADI=0.25, EWP=0.,75	1	2	1	3	3	2	2--3*	1	2	2
CA=0.25, WF=0.75, ADI=0.25, EWP=0.75	1	2	1	3	3	1--2*	3	1	2	2
SNCWF=0.50	1	2	1	3	3	2--3*	3	1	2	2
E=0.25, S=0.50, R=0.25	1	2	1	3	3	1	2	1	3	2

[a] The first row presents vulnerability classes of the baseline index derived by using equal hierarchical weights (EHW). Rows 2-6 show sensitivity tests based on a change in the weights of a number of indicators. The numbers/symbols in each column refer to: 1 - low vulnerability class; 2 - medium vulnerability class; 3 - high vulnerability class; * - value at the border between two classes.

Table 4 Estimated values of agricultural systems vulnerability index (ASVI) under different scenarios with applied equal hierarchical weighting (EHW) method, by district of Khorezm

District	Baseline (2012)	BAU -20%[a]	ADAPT -20%[b]
Shavat	0.65	0.68	0.38
Khushkupir	0.63	0.66	0.41
Khazarasp	0.59	0.60	0.61
Gurlen	0.58	0.61	0.61
Yangibazar	0.56	0.59	0.59
Yangiarik	0.53	0.55	0.30
Urgench	0.52	0.55	0.55
Khanka	0.48	0.50	0.50
Bagat	0.46	0.48	0.48
Khiva	0.45	0.47	0.47

[a] BAU -20% refers to business-as-usual scenario with reduction of water flow by 20%

[b] ADAPT -20% refer to the case of introducing a set of adaptation measures (as described in Section 3.2) in response to the expected 20% less water availability

Supplement 1

Table S1 List of key informants included in survey[a] for exploring the vulnerability to water scarcity in Khorezm region of Uzbekistan

Organization	Field of expertise
International development organization working in the region	Rural development, farmers' adaptation, water and agriculture management
Ministry of Agriculture and Water resources of the Republic of Uzbekistan	Agronomy and water management Agricultural economics Village representative
Regional branch of the State Committee for Natural Protection	Environmental protection, ecological conservation and restoration
Khorezm Administration on Hydrometeorology (Uzhydromet)	Climate and water
Khorezm representative of Farmers' Association of the Republic of Uzbekistan	Farmers' support services (information dissemination, trainings, market access)
Insurance company (Uzagrosugurta)	Natural disaster losses in the agricultural sector (assessment and coverage)
Water Consumer Association	Local representatives from Gurlen and Kushkupir districts

[a] The survey was conducted in April and May 2013 in the Khorezm region of Uzbekistan by the lead author. A total of 10 unique interviews with key informants were performed

Supplement 2

Table S2 Detailed specification of indicators and descriptive statistics

Indicators: description, relevance and data source	Min	Max	Mean	St. dev.
WF (water flow to district, million m^3) Water flow (WF) represents the long-term average water supply to each district which is planned by the government and determined by the water availability and annual crop planning. The values of the average water flow to each district during the vegetation period (1998-2012) were calculated based on data obtained from MAWR (2011)[a] and OblVodkhoz (2013)[b]. The indicator is assumed to be negatively related to the district's vulnerability.	203.13	337.21	266.89	43.28
CA (share of the crop area in the total area of Khorezm, %) The indicator presents the land planned for 1-year cropping as of January 2013 (e.g. fruit trees gardens are multi-year plants thus are not included) and the data is taken from OblVodkhoz (2013)[b]. The indicator reflects which district has higher share crop land within Khorezm, thus is more exposed to climate change and water scarcity.	6.50	12.80	10.00	2.29
PPL (population share in the total population of Khorezm, %) The indicator takes into consideration which districts are more populated and therefore more vulnerable. The data is for 01.01.2013 and originates from OblStat (2013a)[c].	4.66	18.65	10.00	4.12
GAP (district's gross agricultural production share, %) This indicator shows the average gross agricultural production share of each district in the total GAP of the Khorezm, being a proxy for the exposure of the region. The source is OblStat (2013b)[d]. Remark: Even though the available data is for 1999-2012, the rate is calculated using data from 2009 onwards, due to the following factors: (i) new land consolidation reforms towards farm optimization were initiated in 2008, which would have affected farm efficiency and profits; (ii) 2008 was also severe drought year; (iii) even though 2011 was moderate drought year, the links between land reforms and drought impacts are reflected in the growth rate under current land reforms.	7.34	14.11	10.00	1.96
GS (average groundwater salinity, g/l) The indicator shows the long-term average (1990-2004, no later data exists) ground-water salt content for each district. The dataset (ZEF/ UNESCO Project Database)[e] contains in total 1970 collecting points (observation wells) in Khorezm and on average 197 points per district. The samples were taken each year during April, July and October.	1.47	2.26	1.80	0.24
LQCL (share of the low quality crop land in the total district's crop land, %) Official numbers are taken from OblVodkhoz (2013)[b]. Low quality crop land is defined as area with soil infertility. Soil quality conditions in Uzbekistan are measured through soil *bonitet* (an aggregate score in the range 0-100 of several parameters, including results of laboratory analysis) (Akramkhanov et al. 2012)[f].	6.93	18.70	13.55	4.08

Indicators: description, relevance and data source	Min	Max	Mean	St. dev.
The indicator reflects which district has higher share of poor quality soils as of January 2013, which suggests higher susceptibility.				
CWA (share of the cotton/wheat area in the total district's area, %)	69.43	90.67	83.98	5.64
Official numbers are taken from OblVodkhoz (2013)[b] and the indicator reflects which district has higher share of land used for cotton cultivation, thus sensitive to water scarcity (Remark: the values show jointly cotton and wheat area, since separate data for cotton area was not available, however big part of the cotton fields are rotated with winter wheat and therefore is considered suitable indicator variable).				
RA (share of the rice area in the total district's area, %)	4.30	19.59	8.90	5.08
The data source is OblVodkhoz (2013)[b]. During a drought year, rice production is significantly reduced and therefore normal water availability year 2012 is taken to derive the indicator values. Our assumptions suggest that high share of rice areas makes the districts more vulnerable.				
RPPL (share of the rural population in the total for the district, %)	48.04	82.45	69.58	10.44
The values show the districts with dominating rural population, thus more linked with agriculture. The data is as of 01.01.2013 and originate from the OblStat (2013a)[c].				
CRAG (compound rate of agricultural growth per capita)	0.02	0.07	0.03	0.02
The indicator takes 2009-2012 annual gross agricultural output per capita and measures the agricultural development of each district, whereas higher values reflect lower susceptibility. The data specification is same as GAP, including the reasoning for taking 2009-2012 series only. The formula used is as follows: $CRAG = \left((GAP\ per\ cap_{2012}/GAP\ per\ cap_{2009})^{\frac{1}{3}}\right) - 1$				
AI (access to irrigation, category)	1	3	2	
The districts are first divided into 3 categories (upper-tail, mid-tail, end-tail) based on previous research (Bekchanov et al. 2010)[g]. The indicator reflects the location along the main irrigation canals which determines the access to water of each district. Therefore the category variables in this code refer to: 1- low access at the end-tail location (downstream); 2 - medium access at the mid-tail location (midstream) and 3 – high access at the upper-end location (upstream).				
EWP (economic water productivity, USZ/m^{-3})	9.35	18.65	14.31	2.86
The indicator distinguishes which district has higher gross agricultural output per unit of water flow for the period 2009-2012 (i.e. it reflects land use, water use, technical efficiency and capacity). It is expected that the indicator will be positively related to the capacity of the district to optimize the water-use. The calculations are based on the data for WF and GAP, being specified above. The calculated values are similar to previously obtained results from Bekchanov et al. (2010)[g] for districts' water productivity for the period 2000-2007. Difference is observed mainly in the productivity of Urgench and Khazarasp, but the datasets used in this study differ.				

Indicators: description, relevance and data source	Min	Max	Mean	St. dev.
ADI (agricultural diversity index, index) The index is calculated using Shannon's diversity index: $APDI\ (Shannon\ diversity\ index)_i = -\sum_{j=1}^{s} p_j * ln\ p_j$ where, i – district in the Khorezm region, p_j – proportion of land (ha) used for j specialization, s – total land. The main specialization categories included are (the classification is made according to the data obtained from OblVodkhoz (2013)[b]): cotton and wheat; livestock; fruits and vegetables (horticulture; viticulture; watermelon; potatoes; other vegetables); other (silk; poultry; honey makers; fishery). Higher ADI suggests more diversity, thus less vulnerability to climate change and water scarcity.	0.41	0.93	0.58	0.14
SNCWF (share of non-cotton/wheat farms for each district, %) Using the same dataset as ADI, this indicator is a proxy for land tenure and freedom in decision-making, since cotton and wheat farmers are under state quota production system, including strict requirements on the production techniques (fertilizers use, tillage, etc.), as well as lower opportunities for making profit. Therefore, SNCWF is assumed to be negatively related with vulnerability.	46.41	68.51	57.20	6.94

[a] MAWR (2011) Land and Water Use Values for Uzbekistan for 1998–2010. Ministry of Agriculture and Water Resources of the Republic of Uzbekistan

[b] OblVodkhoz (2013) Annual Bulletin, January 2013. Khorezm Regional Department of Agriculture and Water Resources Management. Ministry of Agriculture and Water Resources, Uzbekistan

[c] OblStat (2013a) Socio-economic indicators for Khorezm. Regional Statistical Department, Urgench, Uzbekistan

[d] OblStat (2013b) Agricultural Indicators for Khorezm Oblast. Regional Statistical Department, Urgench, Uzbekistan

[e] ZEF/ UNESCO Project Database

[f] Akramkhanov A, Kuziev R, Sommer R, Martius C, Forkutsa O, Massucati L (2012) Soils and soil ecology in Khorezm. In: Martius C, Rudenko I, Lamers JPA, Vlek PLG (eds) Cotton, water, salts and soums: Economic and ecological restructuring in Khorezm, Uzbekistan, Springer Netherlands

[g] Bekchanov M, Karimov A, Lamers JPA (2010) Impact of water availability on land and water productivity: A temporal and spatial analysis of the case study region Khorezm, Uzbekistan. Water 2 (3):668-684 (Special Issue: Challenges and Developments on Water Resources Management in Central Asia)

Supplement 3

Table S3 Pearson correlation coefficients for the baseline scenario dataset

	WF	**CA**	**PPL**	**GAP**	**GS**	**LQCL**	**CWA**	**RA**	**RPPL**	**CRAG**	**AI**	**EWP**	**ADI**	**SNCWF**
WF	1.00													
CA	0.47	1.00												
PPL	0.17	0.08	1.00											
GAP	0.38	0.43	0.80	1.00										
GS	0.43	-0.10	-0.36	-0.42	1.00									
LQCL	-0.37	-0.30	-0.49	-0.61	0.59	1.00								
CWA	0.25	0.48	-0.65	-0.25	0.15	-0.01	1.00							
RA	-0.13	0.42	-0.18	0.26	-0.25	0.01	0.16	1.00						
RPPL	-0.38	-0.47	-0.70	-0.89	0.34	0.62	0.20	-0.34	1.00					
CRAG	0.16	-0.04	0.50	0.27	-0.32	-0.55	-0.33	-0.43	-0.29	1.00				
AI	-0.07	0.40	-0.05	0.32	-0.64	-0.48	0.31	0.56	-0.15	-0.18	1.00			
EWP	-0.45	0.08	0.62	0.63	-0.74	-0.24	-0.46	0.41	-0.51	0.03	0.43	1.00		
ADI	-0.26	-0.54	0.60	0.18	-0.08	0.07	-0.99	-0.19	-0.13	0.31	-0.35	0.40	1.00	
SNCWF	-0.25	-0.76	0.24	-0.14	0.26	0.33	-0.52	-0.49	0.31	-0.10	-0.38	0.07	0.59	1.00

Supplement 4

Table S4 Summary of the results of the baseline agricultural systems vulnerability assessment for Khorezm – a detailed characterization by district

District	Level of vulnerability and key factors
Bagat	**Vulnerability: low**. The baseline scenario rank of Bagat is 9, suggesting one of the lowest levels of vulnerability in the region. Overall, Bagat has low exposure and high resilience in comparison with the other regions. Meanwhile, the susceptibility falls in the mid-class, shaped primary by the highest for Khorezm dependence and development, i.e. RPPL and CRAG indicators.
Gurlen	**Vulnerability: medium**. Gurlen, even though located close to the river, has medium exposure, susceptibility and very low resilience. To this contribute the high values of the indicators CA, GAP and the huge land used for cotton and wheat, including the lowest share of non-cotton farms. Major susceptibility factor is also the largest share of the land used for rice cultivation.
Khanka	**Vulnerability: low**. Khanka district has the lowest susceptibility in Khorezm, associated with the lowest environmental deterioration, the highest value of CRAG indicator and its upstream location. Despite the medium exposure and the high lack of resilience as a result of the low agricultural diversity and the high share of cotton and wheat farms, the low susceptibility place the district in the low vulnerability class.
Khazarasp	**Vulnerability: high**. Khazarasp is the largest district and has the largest share of crop land which contributes to the high exposure. Susceptibility of the region, however, is medium, shaped by the low CRAG value and the high agricultural production sensitivity due to the intense cropping of cotton and rice (Khazarasp and Gurlen are the largest rice producers in Khorezm). Even though the district has the highest economic water productivity within the region, the low agricultural production diversification places the region in the mid-range of the resilience class.
Khiva	**Vulnerability: low**. Khiva is the district with the highest resilience in Khorezm due to the high agricultural diversity and economic water productivity. Meantime, the district has the smallest share of land used for cotton and wheat cultivation.
Kushkupir	**Vulnerability: high**. Kushkupir holds a big share in the Khorezm crop land, and the same time has the lowest water availability and contributes little to the regional GAP. The high exposure and the medium susceptibility and lack of resilience, make Kushkupir the second most vulnerable district. Together with Shavat, the region has the highest environmental degradation and poorest land and water resources quality – a situation aggravated by the high share of cotton production. Importantly, the region has the lowest economic water productivity.

Shavat	**Vulnerability: high**. Shavat share the same environmental and water access challenges as Kushkupir, as well as the high scale of cotton production given the poor state of its natural resources. Water flow to the district however is higher in comparison to Kushkupir, which places Shavat in the mid-class of exposure component.
Urgench	**Vulnerability: low to medium**. Urgench is the Khorezm regional centre, with the highest values of PPL and GAP indicators, and at the same time it holds a large share of Khorezm's crop land. All of those factors contribute to the highest value of exposure within the region. However the district have very low susceptibility related to the better state of land and water resources and highest share of urban population in comparison with the rest of the districts. The lack of resilience sub-index of Urgench is in the lower range of mid-class.
Yangiarik	**Vulnerability: medium**. Yangiarik is a downstream district, with the highest regional susceptibility sub-index, main determinants of which are the poor environmental quality, the high share of cotton and wheat fields, as well as the dominance of the rural population and the lower agricultural development rate. However, Yangiarik is the least exposed district, having the lowest CA and GAP indicators values. The district has medium resilience.
Yangibazar	**Vulnerability: medium**. Similarly to Yangiarik, Yangibazar has very low level of exposure, primary determined by the lowest socio-economic exposure component (PPL and GAP indicators). Meantime, the region has high susceptibility and lack of resilience, with the following most critical factors: the highest share of cotton/wheat area, very high share of rural population, mid-stream location and the lowest agricultural production diversity.