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The Management of Climate Change Impacts on Groundwater and dependent Ecosystems: A Regional Assessment Approach

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Abstract

Climate change impact on the global hydrological cycle is increasingly becoming profound in human societies. In particular, changes in regional groundwater quantity and quality are now a major concern to human societies and livelihoods in the coastal regions where about 70% of the world population resides, and in the arid and semi-arid regions where freshwater is already a crucial resource for survival (BGR, 2008; Voudouris et al., 2010 and Abd-Elhamid, 2010). Moreover, recent empirical and assessment evidence revealed that changes in groundwater conditions due to climate changes and human activities (e.g., unsustainable extraction of groundwater, irrigation, waste and pollutants disposal, urbanization and land use changes) would undermine the usefulness of groundwater for domestic, industry, and agricultural purposes. Hence, this paper attempts to improve the understanding of groundwater systems and likely changes due to natural and anthropogenic pressures, as well as provide a systemic approach to sustainable and proactive management of regional groundwater resources. This paper proposes a spatially resolved Relative Risk Assessment (RRA) approach to enhancing the understanding of groundwater resources and their dynamics due to regional climate changes. The paper describes RRA functionalities and procedures for systemic analysis of climate change impacts- vulnerability and risks on groundwater and dependent ecosystems according to an ecosystem perspective. This allows to consider relevant socio-economic and hydrogeological vulnerability, impacts and risks indicators with the aim to estimate effectively impacts on groundwater systems. Thus, provides valid support for national and regional water authorities in examining the possible consequences of changes in key environmental parameters, as well as aids relevant management practices, such as Integrated Water Resources Management (IWRM) and Integrated Coastal Zone Management (ICZM) etc.

Keywords: Groundwater Systems, Relative Risk Assessment, Climate Change.

1.0 Introduction

Groundwater resources, including those in the coastal regions, are widely recognized as both strategic freshwater sources and the world's largest reservoir of accessible freshwater for numerous purposes (BGR, 2008; Zbigniew and Doll, 2009; Abd-Elbamid, H.F, 2010). Groundwater provides about 75% of the drinking water in the European Union, about 80% of the rural water supply in Sub-Sahara Africa and about 60% of the water supply for agricultural purposes in India (Klove et al., 2011). Moreover, groundwater is a reliable and indispensable source of freshwater along the Mediterranean coast, where presently about 400 million people live, and in addition, the region is visited by about 200 million international visitors on an annual basis (Baba and Tayfur, 2011). Groundwater may become essentially important in the advent of an extreme dry climate that would increase the need for safe, clean and portable water due to the decline in natural water table levels (Iyalomhe F., et al. 2015). Therefore, groundwater resources are not only invaluable for human welfare and development, but they are also ideal resources for socio-ecological functions (Danielopol et al., 2003; Goderniaux, P., 2010; Klove et al., 2011).

The potential climate change effects on coastal groundwater resources, particularly at the regional/local scale, are still not clear, due to uncertainty related to projections for climate variables and the lack of integrated modelling of the hydrological cycle, including the interactions of surface and subsurface water resources (Baruffi et al., 2012). This lack of relevant information has reduced the ability to study and understand climate-related impacts on regional groundwater resources and its consequent effects on dependent ecosystems (Iyalomhe F., et al., 2015). Moreover, the understanding- the global hydrological cycle is inextricably linked to the climate system further signifies that water resources, especially groundwater aquifers will be prone to the effects of climate change and consequent effects of environmental and social stresses, further established that climate change has already and will increasingly impact water resources especially groundwater (in terms of quantity and quality).

The assessment and management of potential climate change effects on water resources and in particular, on groundwater aquifers, present difficult challenges to hydrologists, geologists, and climatologist, and indeed water managers (Baruffi et al. 2012). Such stems from the insufficient or lack of understanding of the relationship between climate change and the global hydrological cycle, which is largely due to the inadequate representation of subsurface flows and groundwater recharges processes that cause additional complexity that is often neglected and over-simplified by several studies (Goderniaux, 2010). However, it is crucial to protect and preserve groundwater resources and more importantly adapt them to the present and future climate changes and unsustainable human actions, because preventing groundwater degradation and unsustainable exploitation will prove more efficient than trying to clean up and restore contaminated aquifers or wells. This recognition calls for the development and application of relevant interdisciplinary methodologies and approaches useful to protect and manage groundwater resources and to achieve a better understanding of the relationship between climate change and groundwater systems, and thus sustain the renewable capacity of freshwater. In addition, the indispensability of groundwater resources for human survival, mostly in arid and semi-arid regions, has further underscored the need for such methodologies and their application.

Accordingly, this paper proposes a spatially resolved Relative Risk Assessment (RRA) method that identifies all the necessary components involved in impacts and risks analyses, including their possible relationship at the regional scale. It considers multiple habitats, multiple sources releasing a range of stressors that can impact multiple endpoints (Landis, 2005). The spatially resolved RRA is based on a regional risk assessment conceptual framework (Figure 2) applied to evaluate potential climate change impacts on groundwater and associated natural and human systems through the characterization of climate change hazard scenarios and the assessment of exposure, susceptibility, risks, and damages.

The RRA method considers relevant socio-economic and hydrogeological vulnerability, impacts and risks indicators with the aim to estimate effectively impacts on coastal groundwater systems. Traditionally, regional risk assessment procedure aims at providing a quantitative and systematic approach to estimate and compare the impacts of environmental problems, which affect large geographic areas (Hunsaker et al., 1990). In this paper, the RRA is defined specifically as an integrated risk assessment procedure that considers the presence of multiple habitats, multiple sources that could release multiple stressors, which impact on multiple endpoints, and the characteristics of the landscape (Landis, 2005). It concerns the use of Multi Criteria Decision Analysis (MCDA) techniques, to estimate the relative risks in the considered region, compare different impacts and stressors, rank targets and exposure units at risk, and select those risks that need to be investigated thoroughly.
Also, the RRA considers the preliminary definition of framework (Figure 1) for the integrated analysis of climate change impacts and risks on groundwater and for the conceptual assessment of regional climate change impacts and risks. Such framework represents the main relationships between natural and anthropogenic forcing, generated stressors and consequent environmental and socio-economic impacts. This is used to analyse relevant impacts on surface and sub-surface waters and to identify the multiple relationships between impacts on socio-economic systems and biodiversity, by integrating relevant environmental features and their complex interactions based on an ecosystem approach. The framework serves as guideline for integrating tools and methods for the application of the spatially resolved methodology and for identifying relevant impacts and risks to be further analysed.

1.1 Climate Change Impacts Framework for Groundwater Systems

The framework for integrated analysis and management of impacts and risks related to climate change on groundwater and dependent ecosystems (Figure 1) represents main relationships between the primary drivers (climatic) of the natural and anthropogenic stressors, and the environmental and socioeconomic impacts generated.

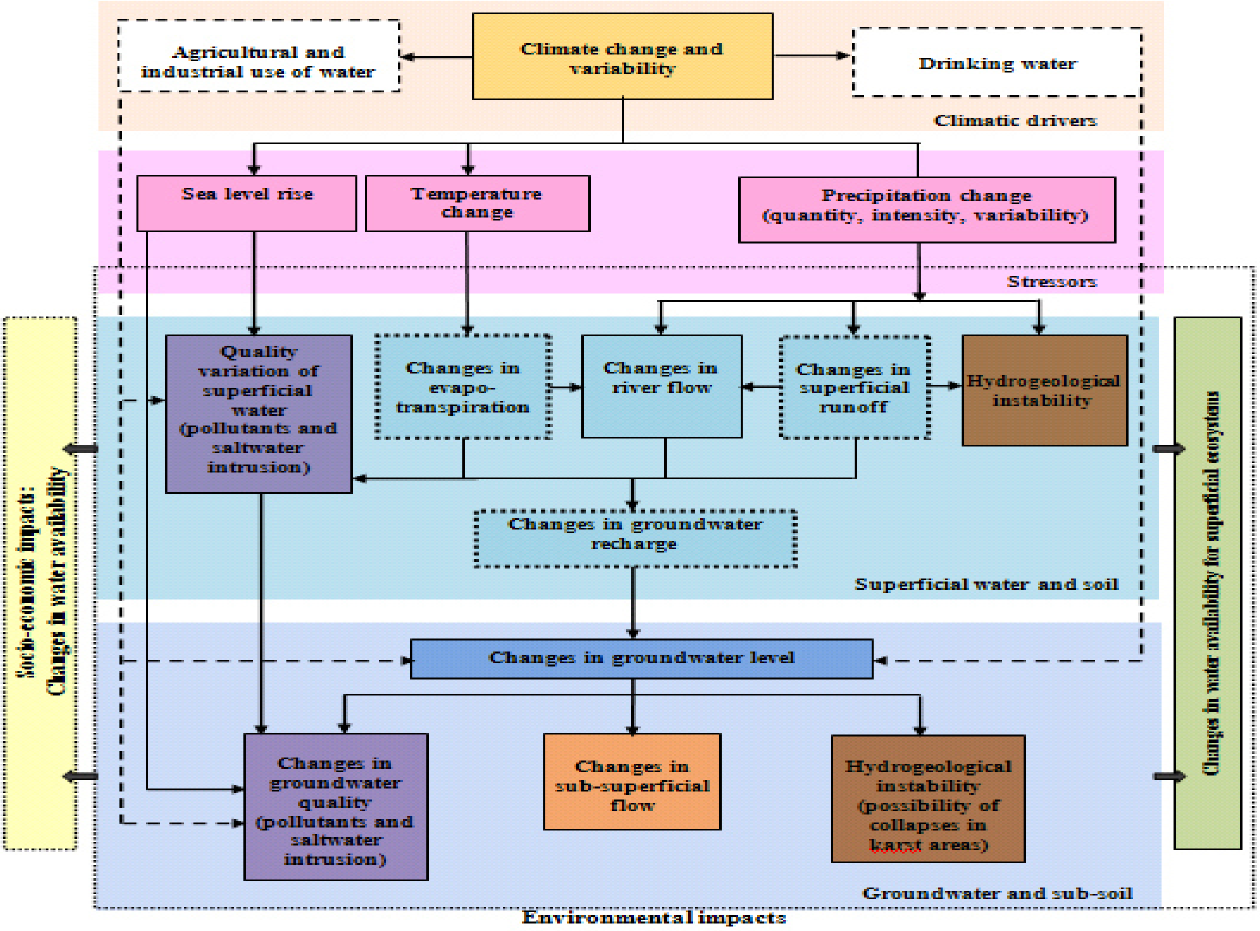

Figure 1. Framework describing cause and effect relationships among forcing, stressors, and socioeconomic and environmental impacts of climate change on groundwater and related systems.

Starting from the forcing, climate change has been identified as generating major stressors of environmental impacts on water resources. These are then divided into two main areas, the superficial water and soil and the groundwater and subsoil, considering the relationship between surface water and groundwater which underpins the assessment of impacts on groundwater and the evaluation of potential climate change impacts on surface water resources and related ecosystems. The stressors identified within the framework are linked to changes in sea levels, temperatures and precipitation (amount, intensity and variability), while the main impacts are those that relate to *variations in the quality of water resources*, especially variations in the recharge process and groundwater levels. For surface water resources, the variations in recharge are mainly due to changes in the flow of water bodies, which are important sources of groundwater recharge. These variations in flow rates of water bodies are influenced by changes in precipitation, surface runoff and evapotranspiration, which in turn depend on the variations in temperatures. The changes that occurred at the level of evapotranspiration, surface runoff and groundwater recharge, should be considered as processes under the influence of anthropogenic stressors that can lead to changes in impacts and conditions of receptors, rather than being actual impacts. Thus, changes in the recharge process result in changes in the groundwater levels, which are already strongly influenced by other anthropogenic forcing. The consequences of this variation in water resources quantity are many and may include changes in the direction of groundwater flows, the increase in landslides and changes in water quality (e.g. increase in the concentration of pollutants like saline or nitrate). The impacts related to *changes in water quality* are due to changes in the dilution of pollutants and increased concentration of solutes, linked to the intrusion of saltwater that affects both surface water and groundwater resources. Changes in water quality impacts are due to increased sea levels that support the phenomenon of saltwater intrusion mostly in coastal aquifers, and the variations in precipitation that can lead to a greater leaching of soil. These often result in the increased transportation of chemicals and the less dilution of pollutants in water. The quality of groundwater resources depends on the quality of surface waters that constitute its recharge and the anthropogenic forcing, especially in regard to the use of water in agriculture and industry processes, and also land use/cover changes via mining and quarry activities. The impacts due to *landslides or collapse of slope and karst areas* can affect both the surface and the subsoil. On the surface the main problems are caused by changes in water quantity, deriving from changes in intensity of rainfall and the resultant surface runoff, which may depends on changes in land use and land cover or vegetation, leading to phenomena of slope instability. With regard to the subsoil, however, the main causes of damage are due to groundwater level variations, generally in karst areas. In addition, there are significant *impacts on biodiversity and socio-economic aspects* of the environment. For example, the impacts on biodiversity stem from variations in availability of water for ecosystems that can lead to a variation or loss of both habitats and species. The impacts on socioeconomic systems are mainly due to changes in water availability for domestic, agriculture, industries, and recreations needs. These impacts depend largely on the quantity and quality of groundwater and surface water resources.

This framework can be applied to the study of different environmental systems and to finalize the analysis of their impacts and risks. However, it emerged that climate change has already affected and will continue to affect the quantity and quality of groundwater resources, which largely depend on changes in meteorological variables and land use, vegetation cover and soil properties.

1.1.1 The Spatially resolved RRA Conceptual Framework

The conceptual RRA framework shown in (Figure 2) complies with the Source-Pathway-Receptor-Consequence (SPRC) approach, which allows to evaluate multiple sources of hazards (i.e. climate change and anthropic stressors) that may affect multiple receptors, e.g., wells, rivers, lakes, agricultural areas and natural systems etc., through different patterns of pathways, with the purpose of identifying and ranking potential impacts, exposed targets and areas at risk in the region. For this purpose, the framework consists of three main phases: the scenarios construction phase, which is aimed at the definition of future hazard scenarios for the case study area; the integrated impact and risk assessment phase, which is aimed at the prioritization of impacts, targets and affected areas; and the risk and impact management phase, which is devoted to the definition of adaptation strategies based on relevant indicators aimed to support the reduction of risks and impacts, according to ICZM principles. Accordingly, the RRA conceptual framework represents one of the essential guidelines for the development and application of a spatially resolved RRA, by aggregating two main components: *climate change hazards* (described as scenarios) and *vulnerability* of the region, in the final estimation of risk.

Climate change hazards represent the physical manifestation of climatic variability or changes that may cause the loss of life or social and economic disruption or environmental degradation (e.g. droughts, floods, storms, episodes of heavy rainfall, sea-level rise inundation). Basic data that support hazard analysis include numerical climate simulations running at the global and the sub-continental scales, and the simulations of cascading physical processes performed by high-resolution numerical modelling of the region (e.g. hydrodynamic, hydrogeological and hydrological). Numerical models' simulations used for the characterization of hazards are related to different scenarios of greenhouse gas emissions and aerosols (e.g. IPCC scenarios A1 or A1B) that reflect changes in the major driving forces, such as demography, economy, technology, energy and agriculture (Nakicenovic et al., 2000). Moreover, these models' simulations are associated to specific periods (e.g. short or long frame scenarios), reflecting the temporal scales of simulation. Finally, information from these models simulations is used to construct hazard scenarios, including that of observations and time series analyses of climatic parameters' mean and extreme events. This information is aggregated to define relevant *hazard metrics,* which are relevant statistics useful to characterize climate change hazard and to construct exposure scenarios.

Vulnerability represents a multidisciplinary concept that encompasses the site-specific characteristics (e.g. physical, social, economic, and environmental features) of the region that could increase its sensitivity to hazards. Specifically, in the spatially resolved methodology, vulnerability assessment requires the analysis of several factors: *susceptibility factors* (S_f), *value factors* (V_f), and *pathway factors* (P_f). Susceptibility factors are useful to determine the sensitivity of a receptor/target to climate change related hazards. It is mostly represented by geo-physical, socioeconomic and ecological factors (e.g. geomorphology, sediment budget, vegetation cover) and expresses the degree to which a receptor is affected, either adversely or beneficially by climate-related hazards. Accordingly, susceptibility factors denote the dose-response relationship between the exposure of a receptor to climate change and the resulting effects (Füssel and Klein, 2006). Value factors identify relevant environmental and socio-economic features of receptors/targets that need to be preserved for the interest of the region (e.g. land use, fishing areas, population density and protected areas). Finally, pathway factors refer to the physical characteristics of the receptors (e.g. elevation, distance from coastline, groundwater mean level and saltwater interface depth), which determine the possibility that climate change hazards would occur, and thus will support the identification of potential exposure areas.

Within the spatially resolved RRA method, pathway factors are aggregated with hazard metrics, to construct exposure scenarios according to the exposure function that is applied in the final risk estimation. The susceptibility and value factors are aggregated by means of the Multi Criteria Decision Analysis (MCDA) functions, to estimate the final susceptibility of the region to climate change impacts and the value of each receptor/target to be considered in the final estimation of risk and damage. Also, relevant tools, such as geographical information system (GIS) are used to manage, organize, process, analyse, map and spatially manipulate data to facilitate hazard, vulnerability and risk analysis. Overall, the MCDA is used to aggregate vulnerability and hazard variables/parameters in order to rank targets, areas and risks from climate change at the regional scale, while integrating experts' opinions and judgments directly or indirectly, at each step of the RRA process (i.e. from hazard characterization to risk assessment). Expert opinion is particularly important to select and aggregate functions and to assign scores and weights to vulnerability factors.

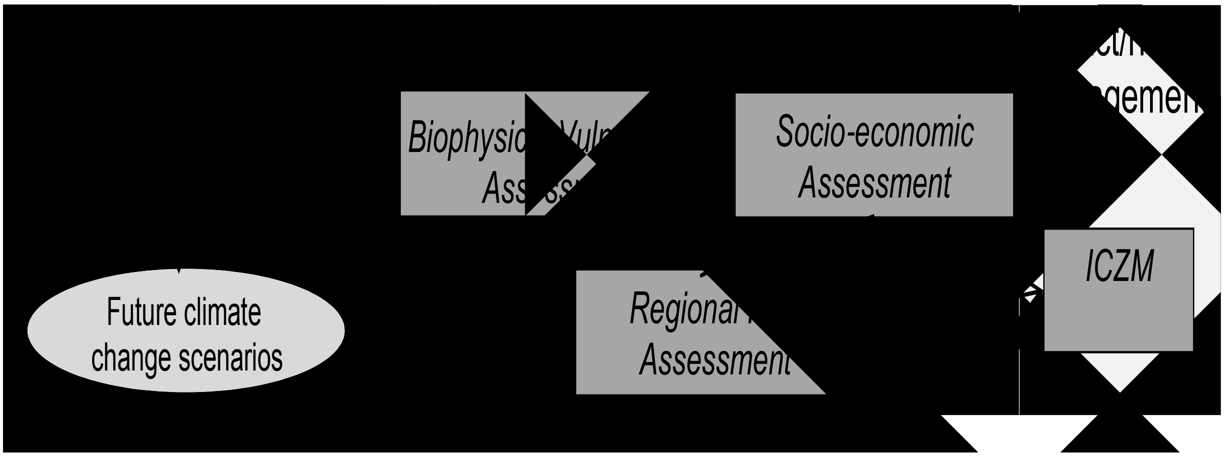

Figure 2. The RRA conceptual frameworks for the analysis of climate change impacts on groundwater at the regional scale.

1.2 Steps for the Spatially Resolved RRA Method

The spatially resolved RRA methodology aims to identify key areas and rank targets/receptors at risk from climate change impacts on the case study area; it considers six major steps:

1. Regional risk matrix
2. Hazard assessment
3. Exposure assessment
4. Susceptibility assessment
5. Risk assessment
6. Damage assessment

1.2.1 Relative Risk Matrixes- Vulnerability and Hazard

The preliminary step to implement the spatially resolved RRA is the definition of a regional risk matrix, which identifies all the components (i.e. stressors, receptors and impacts) contributing to the estimation of risk in the case study area, and their relationships. The regional risk matrix is composed of two distinct matrixes: the vulnerability matrix, which supports the assessment of the case study area's vulnerability to climate change and anthropic related hazards, and the hazard matrix that guides the identification and aggregation of climate related hazard metrics used to construct climate change exposure scenarios. In particular, the hazard matrix allows analysis to identify stressors that contribute to the investigated impacts and the hazard metrics, which are then used to characterize climate change hazards within the hazard assessment step. The vulnerability matrix includes a subset of vulnerability factors- representing physical, ecological and socioeconomic indicators of the considered case study area. These factors are first classified as pathway, susceptibility and value factors and then employed in different stages of the RRA (i.e. exposure, susceptibility, and risk and damage assessment steps).

Typical vulnerability matrix defined for the assessment of climate change impacts represents useful guidelines to identify relevant receptors and/or potential targets within the application area as presented in chapter four. Receptors/targets are important features within the exposure unit, or areas on top of the groundwater bodies. They are natural or anthropogenic systems (e.g. rivers, lakes, agricultural areas, forest and semi-natural environment and wells) of interest due to ecological, economic and social reasons that are not equally affected by climate change hazards (UKCIP, 2003). Each column of the vulnerability matrix includes a subset of vulnerability factors that represent physical, ecological and socio-economic features or indicators applied to assess the spatial vulnerability of each receptor with reference to climate change impacts.

The hazard matrix consists of identified stressors, which are represented by relevant statistics/variables estimated according to the projections of the hydrogeological and hydrological models, based on the IPCC A1B and anthropogenic (actual extraction of groundwater, urbanisation, irrigation and industrial activities) scenarios. Such variables are taken as relevant stressors in relation to the considered climate change hazards, for example, groundwater level variations and saltwater intrusion etc.

1.2.2 Hazard Assessment

Hazard assessment is aimed at the characterization of potential climate change hazard scenarios. In the spatially resolved RRA method, climate change hazard scenarios determine the future conditions of hazards to climatic changes against which a system needs to adapt in order to keep its ecological or socio-economical functions. Moreover, they identify homogeneous hazardous areas that are based on the aggregation of multiple hazard metrics, and are built considering not only changes in the mean state of climate variables but also changes in climate variability and extremes.

The basis of the hazard assessment concerns the definition and application of suitable statistics derived from numerical models and time-series analysis of past measurement of climate variables, to construct scenarios representing potentially significant hazards with reference to climate change. Since the models' forecasts provide a huge amount of outputs for a detailed temporal resolution, the risk assessor needs to define statistics that can properly describe the trend of variables under analysis e.g. mean or average, mode or median of values; cumulative value, and absolute maximum or minimum values that may be recorded over a particular interval of time.

1.2.3 Exposure Assessment

This aims to identify and classify possible exposed/risk prone areas or valuable receptors/targets in the case study area. In the exposure assessment, hazard metrics are normalized through the assignation of scores and weights, and are aggregated with the pathway factors using specific Exposure functions for each impact. The exposure functions are defined for each climate change impact and can be applied to different hazard scenarios that represent the spatial distribution of climate change hazards in a specific timeframe under specific emission scenarios. They are derived from the scientific literature or can be a MCDA function aimed at integrating the hazard metrics reported in the sub-cells of the hazard matrix with the pathway factors reported in the sub-cells of the vulnerability matrix. The Exposure functions applied for the assessment of exposure are associated with impacts and scenarios defined for the case study area.

The hazard metrics chosen for the exposure assessment can be normalized with the assignation of scores and weights, if they are required specifically in the Exposure function. However, hazard classes are related to hazard metrics and represent different intensities of hazard to climatic stressors with reference to each impact. Classes can be categorical (e.g. presence or absence of a particular indicator or indicator type) or can be derived from continuous data. To each class, a score is assigned from a minimum value (i.e. 0) to a maximum value (i.e.1), with minimum representing no hazard or exposure and the maximum value representing higher exposure to hazard compared to the others. Experts assign intermediate scores between 0 and 1 to represent moderate hazard or exposure. Moreover, weights (in the range 0–1) can be assigned by experts to hazard metrics, to represent their relative importance in the final estimation of exposure with reference to each impact.

1.2.4 Susceptibility Assessment

This provides an estimation of the case study area' sensitivity to climate related hazards. The Susceptibility assessment requires the aggregation of susceptibility factors that are first normalized through the assignation of scores and weights and then aggregated by means of appropriate MCDA functions (Probabilistic-or). This aims to estimate the spatial susceptibility of the case study area that can be characterized by two or more receptors/targets, according to the susceptibility function defined for all the susceptibility factors in the vulnerability matrix for the considered impacts. In this way, susceptibility will be evaluated considering the contributions of all the susceptibility factors related to the sub-cell taken only once.

In particular, to apply the susceptibility function the susceptibility factors must first be normalized according to relevant literature and expert judgments. Thresholds that reflect variations in the degree to which the examined receptors/targets may be affected by a climate-related impact determine susceptibility factor classification. Thus, scores related to susceptibility factors' classes represent different degrees of possibility to which these receptors could be affected by climate-related hazards in consideration of different impacts. The assignation of scores to susceptibility classes falls in the range of 0 (i.e. no susceptibility) to 1 (i.e. maximum susceptibility). Moreover, individual susceptibility factors can be weighted to represent their relative importance in the final estimation of susceptibility with reference to each impact.

1.2.5 Risk Assessment

This is aimed at identifying and classifying areas and targets at risk from different climate change impacts in the considered region. Accordingly, risk assessment result in the estimation of relative risks scores via the integration of information regarding the exposure to a given climate change hazard with the susceptibility of receptors/targets to the examined hazard. Relative risk scores are not absolute predictions about the risks related to climate change. Rather they provide relative classifications about areas and targets that are likely to be affected by climate change impacts more severely than others in the same region.

The general function for the estimation of relative risk in relation to impact is the product of exposure scores-(representing the exposure associated to a given climate change hazard scenario) and the susceptibility scores-(representing the degree to which a receptor is affected by climate-related stimuli).

Risk score varies from 0 to 1, in which 0 means that in an area there is no risk (i.e. there is no exposure or no sensitivity) and 1 means higher risk for the considered targets/areas in the considered region with reference to impacts and scenarios. The risk score could be associated to each receptor ***i*** considering the cells of the territory associated to that receptor. Finally, the Risk function allows evaluating statistics (e.g. total surface and percentage of surface associated to each risk class) useful to support the decision makers in the definition of adaptation measures.

1.2.6 Damage Assessment

Damage assessment aggregates the results of risk assessment with the results of the assessment of environmental and socio-economic values of receptors/targets, to provide an estimation of the social, economic and environmental losses associated to targets and areas at risk in the considered region. Aggregating the value factors, included in the vulnerability matrix, by means of MCDA functions, performs the estimation of receptors' values. To estimate the value associated to each receptor, the value factors must be normalized through the assignation of scores and weights. Specifically, value factors must first be classified to reflect variations in the environmental or socio-economic values associated to each receptor. Then, scores in the 0-1 ranges must be assigned to each value class to represent the relative importance (i.e. the socio-economic or environmental features) of each single class compared to the others. Finally, value factor scores are weighted to represent the relative importance of each value factor in the estimation of the values associated to receptors. Decision makers perform the assignation of scores and weights to value classes. Normalized value factor scores are then aggregated by mean of a specific Value function, to estimate the value associated to each receptor/targets. The main aim of the Value function is to identify and prioritize relevant environmental and socio-economic features of the receptors that need to be preserved for the interest of the region.

Thus, damage assessment aggregates relative risk scores estimated for each impact and scenarios with the value scores associated to each target through the Damage function.

The Damage scores vary from 0 to 1. It assumes the higher score when risks are higher (i.e.1) and the value score is high, and assumes the minimum value (i.e. 0) when risks and/or the value are low (i.e. 0). In the other cases, the damage score assumes values in the range 0-1, and allows to identifying and prioritizing the potential losses associated to targets and areas at risk in the considered region, and supporting the identification of areas, which require prior adaptation actions. The damage scores are calculated for all the spatial units of the examined region where receptors/targets are located, and allows the estimation of relevant statistics (e.g. percentage of the receptor surface associated to each damage class and total surface of the receptor with higher damage scores for each administrative unit), useful to support the decision makers in the definition and prioritization of adaptation measures.

1.3 Outputs of the Spatially Resolved RRA Method

The main outputs of the spatially resolved RRA include GIS-based **exposure**, **risk** and **damage** maps that are calculated through the application of exposure, susceptibility, and risk and damage functions described in the steps of the methodology. These maps allow the definition of planning and management strategies by establishing relative indicators for intervention, identifying suitable areas for human settlements, infrastructures and economic activities, and provide a basis for land use planning within the case study area.

The hazard metrics and the vulnerability factors identified for the case study area are represented in raster GIS layers, which allow the analysis and visualization of their spatial distribution in the case study area. Thus, the outputs of the risk assessment are raster maps (i.e. cell based maps) representing the spatial distribution of exposure, susceptibility, risk and damage. According to Figure 3, exposure maps represent climate change hazard scenarios based on the aggregation of hazard metrics with pathway factors. Susceptibility maps represent the spatial distribution of environmental and socio-economic susceptibility factors, and are derived from the aggregation of these factors. Risk maps allow analysts to identify and rank of areas and receptors at risk from climate change related impacts in the considered region, and are obtained from the overlay of exposure and susceptibility maps. The final outputs are damage maps, which are derived from the overlay of the risk maps and the value maps (obtained from the aggregation of value factors). Damage maps allow analysts to identify and rank areas and receptors prone to damages from climate change related impacts in the considered region.

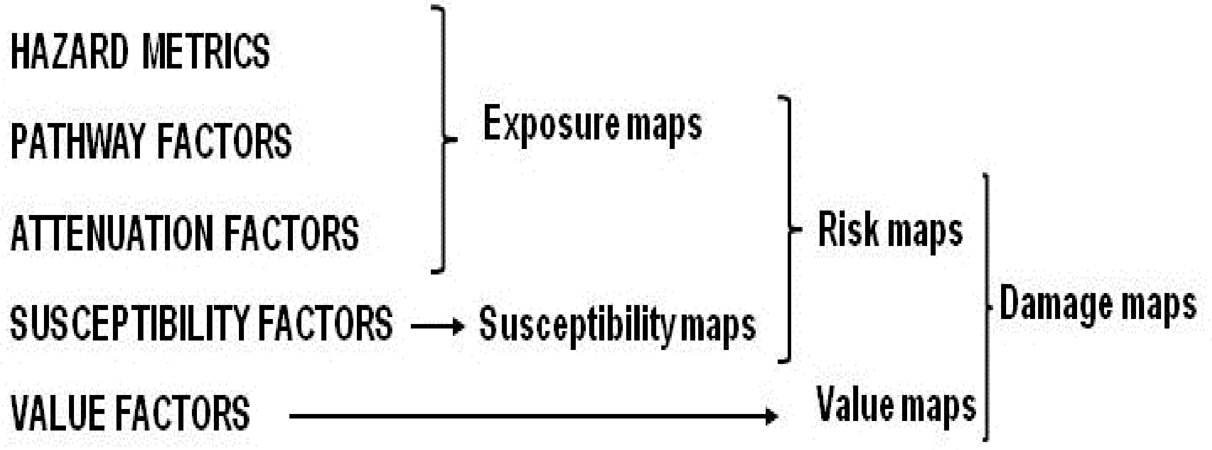

Figure 3. Output maps scheme for spatially resolved RRA methodology

1.4 Conclusions

This paper proposed a spatially resolved RRA method to further support and strengthens the integrated management of climate change impacts on groundwater resources and provides indications for the protection of groundwater-dependent ecosystems at the regional scale.

The method offers a wide range of functionalities that can support the assessment of problems that affect groundwater dependent ecosystems in relation to climate change, for example, it considers the conceptual RRA and groundwater integrated impacts frameworks, which allow analysts to integrate information related to climate change hazards with the vulnerability of the dependent ecosystems. This method also considers relevant outputs from the simulation of climate, hydrology, hydraulic and groundwater systems and regional analysis of physical, socio-ecological and environmental features of the region; and the application of a relative risk model that applies the MCDA techniques, to evaluate climate change impacts and rank targets and areas at risk.

The implementation of this method within the GIS-based decision support tools makes it possible to present relevant outputs as GIS maps (exposure, risk, susceptibility and damage), which on the one hand, support the easy visualization and understanding of groundwater systems dynamics due to climate change and anthropogenic pressures, and on the other, provide relative indicators to establish priorities for intervention and definition of adaptation strategies for sustainable management of groundwater resources. Future studies should look at how this approach could be employ to implement an empirical analysis, in order to verify its efficacy in terms of results- weather they are akin to existing approaches and methodologies.

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