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ASSESSMENT OF ENVIRONMENTAL IMPACTS AND RISKS RELATED TO CLIMATE CHANGE

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PhD Dissertation

ASSESSMENT OF ENVIRONMENTAL IMPACTS AND RISKS RELATED TO CLIMATE CHANGE

By

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Felix Iyalomhe

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LIST OF ACRONYMS

CCIA	Climate change impacts assessment
CCAP	Climate change adaptation project
CMCC	Euro-Mediterranean centre for climate change
COP	Communities of practice
CVR	Venice research consortium
DANIDA	Danish development agency
DSSs	Decision support systems
DESYCO	DEcision support SYstem for COastal climate change impact assessment
ERB	Esino River basin
GCM	Global circulation model
GIS	Geographical information system
GLV	Groundwater level variation
GD	Groundwater directive
HM	Hazard matrix
ICZM	Integrated coastal zone management
IRM	Inductive reflection method
IPCC	Intergovernmental panel on climate change
IWRM	Integrated water resources management
MCDA	Multi-criteria decision analysis
RCM	Regional circulation model
RRA	Regional risk assessment
RRM	Regional risk matrix
RR	Relative risk
RRD	Red river delta
SPRC	Source-pathway-receptor-consequence
SPI	Science-policy interface
SI	Saltwater intrusion
VF	Vulnerability factor
VM	Vulnerability matrix
WFD	Water Framework Directive
WRI	World Resources Institute

SUMMARY

This PhD thesis examines state-of-the-art approaches applied with decision support systems (DSSs) to study climate change effects on coastal systems at the European and international levels. It applies a spatially resolved regional risk assessment (RRA) methodology to evaluate potential climate change related impacts on coastal groundwater aquifer and consequent risks for dependent ecosystems. Also it proposes and reflects on a new approach to successful relations in the science-policy interface aimed at climate change adaptation. Hence there are four specific undertakings:

1. The analysis of GIS-based decision support systems aimed at addressing climate change impacts on coastal waters and related ecosystems;
2. The refinement and adaptation of the regional risk assessment approach to coastal groundwater resources' issues caused by climate change and anthropogenic pressures;
3. The application of a spatially resolved RRA methodology with the GIS-based DEcision support SYstem for COastal climate change impacts assessment (DESYCO tool), to identify climate change related threats on coastal aquifer and dependent ecosystems, and to particularly rank areas at risk in the lower Esino River valley in the Marche region in Italy;
4. The application of communities of practice theory to examine two model cases, to highlight areas of potential opportunities of and in disagreements with the theory, and to understand how a successful science-policy interface in the climate change adaptation arena could be envisioned as a community of practice.

Firstly, the thesis selects twenty DSSs via a survey of literature and examines such according to the defined specific criteria, to describe and evaluate their actual applicability. The analysis highlighted the relevance of developing climate change impact assessment and management at the regional scale (i.e. subnational and local), according to the requirements of policy and regulatory frameworks, and to the methodological and technical features of the considered DSSs. Most of the examined DSSs show a regional to local applicability with a moderate to high flexibility, and prove to support the evaluation of climate change impacts via relevant functionalities. However, these DSSs were applied to analyse particular climate change impact on coastal sectors (15 out of the 20 DSS), regardless of the complexity and interrelatedness of coastal systems' impacts.

Secondly, the thesis considers the conceptual regional risk assessment and groundwater impacts integrated frameworks, to implement relevant outputs from climate, hydrological and hydrogeological models that were applied to the lower Esino River basin, at the global and sub-continental scales. The models' outputs (i.e. projections in climate variables) were used to develop potential hazards metrics that were specifically defined according to different precipitation projections with reference to seasons. These metrics were used to analyse consequent effects of

changes in groundwater quantity and quality at the basin scale using the spatially resolved methodology. This methodology employed several assessment steps (i.e. hazard, exposure, susceptibility, risk and damage), which were implemented with the GIS-based DESYCO tool, to characterize relative risks from changes in groundwater quantity and quality on coastal groundwater-dependent ecosystems (e.g. wells, river, agricultural areas, lakes, and forests and semi-natural environments), in the lower Esino River valley, considering the defined hazard metrics and indicators/indices used to construct potential climate change scenarios and analyse relevant impacts. Groundwater Level Variations (GLV) and Saltwater Intrusion (SI) impacts were evaluated by the regional scale analysis of climate change impacts on coastal groundwater aquifer and dependent ecosystems. This employed the aggregation of the lower Esino River valley's vulnerability assessment (i.e. physical, social, economic and environmental factors) with the defined climate change scenarios, constructed according to precipitation projections with reference to seasons for the 2070-2100 timeframe, based on IPCC A1B emission scenarios. Significant results from the analysis highlight that potential climate changes will exert slight difference in impacts on the lower Esino River valley. In summer, there will be limited direct effects from GLV on specific agricultural areas and natural systems located along the coastline and surface water bodies. That is to say, less than 5% of the total exposed surface of agricultural areas and 50% of natural systems will be at high risk. Superficial water bodies will experience more direct consequences through decline in groundwater depth in the summer. About 40% of total exposed surface of the Esino River and 20% of the lakes will be at very high risk of GLV impacts. Moreover, saltwater intrusion impacts will be restricted to the coastal strip, and thus will exert very limited effects on the Esino coastal aquifer in the future seasons and fewer indirect consequences for dependent ecosystems.

Thirdly, the thesis applies the communities of practice theory in a new way, by examining two climate change adaptation projects (e.g. SALT in Italy and Red River Delta in Vietnam) as model cases. The purpose is to highlight areas of potential opportunities of and in disagreements with the theory, and to understand how a successful science-policy interface in these projects could be envisioned as a community of practice. The assumption is that the social contexts in which these projects exist could be established by the concepts of 'communities of practice,' which defines activities as social processes and historical practices that engage researchers and experts on the one hand, and experts, managers and local stakeholders on the other. The cases were compiled from open-ended surveys, interactive research experience and observation, and were inductively reflected on vis-**à**-vis communities of practice. The model cases revealed challenges as well as potential opportunities for communities of practice. They exist within a middle space (social context) that could facilitate personal and professional relationships, promote formal and informal interactions, needed to negotiate different expertise and narrow apparent boundaries. The thesis concludes that vigorous and dynamic communities of practice promise to nurture the social context in which participants in adaptation

projects are potentially engaged, and thus provide a provisional support to the science-policy interface.

Keywords: Climate change, coastal groundwater aquifer, Esino River basin, regional risk assessment, GIS-based DESYCO, MCDA, communities of practice, groundwater-dependent ecosystems, science-policy interface, social context, climate change adaptation projects, inductive reflection, groundwater level variation, saltwater intrusion, relative risks model

CHAPTER 1

1. INTRODUCTION

1.1 MOTIVATION

The current understanding of changes in water resources' quality and quantity are emerging as one of the major challenges of the 21st century (WRI, 2013), which has established several research initiatives and approaches aimed at the holistic understanding of water resources' issues and consequent effects on related ecosystems. Such approaches could be useful to support vital ecosystems' protection and management in the advent of climate changes and increasing pressures from socioeconomic activities, particularly in the coastal communities. This thesis was specifically inspired by the increasing need for such approaches that could be apply to recent developments in the lower Esino River valley in the Marche region in central Italy. In particular, in the Ancona and Jesi coastal communities where regional water resources are compromised in central Italy, due to the continual urbanization of territory, the incorrect management of urban wastewater, the increasing use of fertilizers in agriculture, and the alteration produced by improper management of river areas and total destruction of vegetation. These problems coupled with the uncontrolled exploitation and pollution of groundwater will alter the chemical-physical characteristics of water resources, and thus irreversibly compromise both the natural conditions of water systems and the development of many human activities in the region. For example, the uncontrolled exploitation of freshwater from the region's coastal aquifer aggravates saltwater intrusion that is also known as seawater infiltration into the aquifer. This infiltration can be persistent or, more often, temporary. In any case, seawater takes the place of fresh water, which outflows from the aquifer system at about the same speed as the former inflows. The effects of the uncontrolled exploitation of a coastal aquifer are observed when nothing can be done; because when seawater has invaded the aquifer it takes a long timeframe (maybe a decade or more) to restore the state of the aquifer, which is often not possible. Saltwater intrusion into coastal aquifers could be due to the inflow of seawater from the sea (i.e. due to high sea levels) and over-extraction from wells, especially in the dry period. In either case, the result is increased changes in groundwater quality and quantity.

Presently, a large number of coastal aquifers are experiencing seawater/saltwater intrusion problems, for example, the coastal aquifer of Esino River that feeds most of the wells in the lower Esino River basin. However, this phenomenon is not always quantifiable due to lack of data and the fact that huge amounts of water are involved. Moreover, seawater flows into the coast at a slow rate and takes a long timeframe for it to pollute the freshwater coming from the continent. Hence it is necessary to monitor and quantify this phenomenon in order to protect freshwater in the coastal aquifer system, by examining the causes that accelerate the process and defining a feasible method to prevent it. Such methods that support the characterization and prediction of saltwater intrusion into coastal aquifer freshwater, due to the unsustainable use of groundwater from aquifers and changes in the sea levels.

Against this background, the thesis aims to contribute to this significant research need by undertaking the following tasks: (1) The systematic and quantitative characterization of climate change related impacts and risks on the Esino River coastal aquifer and dependent ecosystems, considering the spatially resolved RRA method; (2) the definition and application of potential climate change scenarios with reference to seasons according to relevant outputs from the ensemble modelling of climate, hydrology, and groundwater systems; (3) the definition of relevant indicators and indices according to physical, socio-economic and environmental features of the considered region to support the assessment of coastal groundwater aquifer vulnerability and impacts at the regional scale. Finally, the thesis (4) proposes a new approach to a successful science-policy interface in the climate change adaptation arena that could facilitate and nurture improved interactions and relations between scientists and practitioners through interdisciplinary collaboration in climate change adaptation projects. As a consequence, the thesis provides regional water managers and concerned stakeholders with relative risk indicators that can enable them to identify suitable areas for water facilities, human settlement and infrastructure, and also where urgent adaptation measures could be needed and implemented.

1.2 EFFECTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

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 (IAH, 2006; EC, 2008; 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 200 million international visitors on an annual basis (Baba and Tayfur, 2011). Groundwater may become especially important in the advent of an extreme dry climate, which would increase the need for safe, clean and portable water due to the decline in natural water table levels. As a consequence, 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; UN-WWAP, 2003; Goderniaux, P., 2010; Klove et al., 2011).

Climate change coupled with intense socio-economic activities in the coastal regions will exert huge pressures on coastal groundwater resources. However, the relationship between changes in climate variables and global water resources has until recently only been defined conceptually (Bear, 1999; Bates et al., 2008). Thus, 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 ground 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 (Pasini et al., 2012; Iyalomhe et al., forthcoming). However, the IPCC assessment reports summarize qualitative evidence that natural and human induced climate variability and change will inevitably affect the global hydrological cycle and thus, compromise water resource conditions (U.S. Geological Survey, 2009; Dragoni and Sukhija, 2008) through significant changes in the atmospheric water vapour content, precipitation and evapotranspiration patterns, surface runoff and stream flow that will vary in spatial and temporal scales (Sherif and Singh, 1999; Ranjan et al., 2006; Bate et al., 2008; Ferguson and Gleeson, 2012). These changes will affect groundwater quality and quantity within the subsurface and surface zones, and thus limit its usefulness for human environment and its ecosystems. In addition, a few assessment studies (e.g. Sherif and Singh, 1999) aimed at climate change possible impacts on water resources revealed that global warming is inextricably linked with severe effects on groundwater because groundwater resources are vital components of the hydrological cycle that are an integral part of the climate system. Groundwater would be directly or indirectly affected by climate change via changes in temperature, evapotranspiration and precipitation (Bates et al., 2008; Dragoni and Sukhija, 2008; Herrera-Pantoja and Hiscock, 2008; Abd-Elhamid, 2010). In general, analytical studies aimed at the potential consequences of climate change for water resources have often been limited to surface water resources. In particular, those applied to estimate the direct potential consequences from changes in meteorological variables revealed that temperature changes from global warming will affect the hydrological cycle via direct increases of evapotranspiration and reduced soil moisture (Loaiciga et al., 2000; Yusoff et al., 2002; Eckhardt and Ulbrich, 2003; Kundzewicz and Döll, 2009; Franssen, 2009). This will have a direct influence on the precipitation regime and an indirect influence on the flux and storage of water in surface and subsurface reservoirs (e.g. lakes, streams, soil moisture, and water table level). The changes in precipitation that seem to influence largely the hydrological regime would exert different impacts on groundwater resources, in particular, the unconfined aquifers (i.e. where the water table intersects ground surface), through the recharge process and transport of pathogens and other pollutants (Franssen, 2009; Baba and Tayfur, 2011; Abd-Elhamid, 2010).

Similarly, a few studies that were focused on climate change indirect effects on groundwater resources through variations in the soil moisture (Feddema and Freire, 2001), land cover and land use (Loukas et al., 2002; Vorosmarty et al., 2004; Austin et al., 2010), vegetation cover (Eckhardt and

Ulbrich, 2003) and sea levels (Sherif and Singh, 1999) argue that, for example, if vegetation becomes much sparser then groundwater recharge may increase because evapotranspiration is reduced, although surface runoff may be enhanced. The land use and land cover changes caused by the influences of climatic and anthropogenic pressures will affect groundwater conditions, because of the modifications in hydrogeological features and excessive extraction of groundwater. Also, sea level rise would have serious consequences on groundwater quality because of the direct link between groundwater aquifers and surface water resources (i.e. lakes, rivers and streams) and indirect link through the recharge process (i.e. interaction between surface and subsurface layers). That said, the indirect consequences of climate change would depend largely on specific hydrogeological and soil features that also depend on regional anthropic activities (Herrera-Pantoja and Hiscock, 2008). Thus, groundwater aquifers' unique ecological conditions would contribute to their specific vulnerability or sensitivity to potential climate change and anthropogenic pollutions (Mohammadi et al., 2009). For example, in the Esino River basin, where socio-economic activities already have an adverse impact on the environment and the alluvial aquifer forms the subsurface of the coastline, groundwater is naturally prone to contamination from seawater intrusion and untreated waste from industrial and agricultural activities near the coast (www.lifesalt.it/en/idea.html). The Esino River coastal aquifer, similar to several coastal aquifers, is characterized by a natural gradient because of the seawater density difference, dynamic geologic environment and differential tidal fluctuations (Post, 2005). This promotes the fast deterioration of coastal freshwater quality and potentially makes groundwater unusable for human needs. In view of this, several studies have proposed different approaches to the protection and management of Esino River basin groundwater resources as better measures to preserve the quality of freshwater than remediation measures, which often require huge resources and efforts to restore the state of a polluted aquifer. Moreover, remediation measure is uneconomical and often provides impossible remedy for a polluted aquifer (Abd-Elhamid & Javadi, 2011).

1.3 GROUNDWATER RESOURCES PROTECTION AND MANAGEMENT METHODS AND TOOLS

The estimation and management of potential climate change effects on water resources and in particular, on groundwater aquifers, are very difficult challenges faced by hydrologists, geologists, climatologist and indeed water managers. This challenge stems from the insufficient or lack of understanding of the relationship between climate change and the global hydrological cycle. That in part maybe 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 most 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 tools useful to protect and manage groundwater aquifers 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 the development and application of methodologies that are often categorised into two groups: ***investigation*** and ***control***. The former involves the acquisition of relevant information regarding geophysical and hydro-chemical characteristics of aquifers, useful to investigate impacts like saltwater intrusion; this includes methods, such as geophysical, geochemical, experimental studies and numerical models, sometimes implemented with simulation codes e.g., SUTRA, SEWAT, SWIFT, MOCDENS3D, FEFLOW etc., (Bear, 1999). The latter relates to groundwater pollution control that is increasingly becoming a major challenge because of the huge pressures from human activities and climate change effects on the recharge process. Accordingly, several methods have been adopted over the years to control or prevent groundwater contamination, such as reduction of pumping rates, relocation of pumping wells, use of subsurface barriers, natural recharge, artificial recharge, abstraction of saline water and a combination technique (Abd-Elhamid, 2010).

Relevant techniques are adopted with these methodologies, for example, geophysical, remote sensing, geo-database and geographical information system (GIS), and specific management or control procedures and simulation modelling, which makes it practically possible to derive robust information related to climate change impacts on groundwater resources. In particular, these techniques are useful to estimate a reliable volume of water entering and leaving groundwater aquifers, to further reduce the uncertainty associated with groundwater recharge, and to enhance accurate descriptions of the atmospheric and surface-subsurface processes, which are key elements in the context of climate change impacts on groundwater. Groundwater aquifers directly feed surface water resources and their discharge into rivers or streams may be affected by changes in groundwater levels and consequently affect groundwater quantity. According to Table 1.3A, these methodologies also enhance the understanding of groundwater aquifers' vulnerability and the estimation of potential impacts. Based on climate change research focused on reliable and continuously updated databases.

The investigation and control methods' application also consist of relevant tools, such as indicators and indexes that are useful to monitor climate variations, describe the state of the system, characterize spatial and temporal stressors and drivers that could be climatic and anthropogenic, and identify key vulnerable areas (IPCC, 2007). According to the Organisation for Economic Cooperation and Development (OECD), an indicator is regarded as a parameter or a value derived from multiple parameters, which provides information about a phenomenon whose significance goes beyond the property directly associated with the parameter value (OECD, 1993). The OECD proposed the following definition for index: an index is a set of aggregated and weighted parameters or indicators. The index turns out to be an ideal measure of a complex phenomenon that could not be assessed by a single indicator. Within this context, the OECD proposed a framework linking different indicators called the “Pressure-State-Response” (PSR) model, which was re-elaborated later by the European Environmental Agency (EEA, 1995) in the “Driving-Forces-Pressure-State-Impact-Responses” (DPSIR) framework described in Santoro et al. (2009). The five components of the DPSIR framework can be analysed through the use of suitable indicators, such that the complexity of the environmental dynamics can be captured, without losing the framework’s flexibility, as described in (Agostini et al., 2009). Conversely, Dates et al., (1996) define indicators as “a measurable characteristic that provides evidence of the magnitude of stress, or the degree of exposure to stress, or the degree of ecological response to exposure based on ecological characteristics.” They divided indicators into three groups: early warning indicators: when indicators are able to detect the early signs of change, compliance indicators: when indicators tell us whether the objectives have been achieved for a specific ecosystem (e.g. groundwater), and diagnostic indicators: when indicators provide information on the causes of particular problems (e.g. saltwater intrusion).

In general, an indicator represents phenomena that cannot be measured directly and may aggregate different types of datasets (Agostini et al., 2009). In the field of environmental sciences, indicators are physical, chemical, biological or socio-economic measures that at best represent key elements of a complex ecosystem or environmental issue (http://www.ozcoasts.org.au/glossary/def_i-l.jsp). According to Table 1.3B, vulnerability indicators and indices could reflect the outcome of climate change hazards related to changes in groundwater water levels, saltwater intrusion, and increase in pollutants’ concentrations, or the state of the system before the occurrence of the hazard. In particular, Table 1.3B highlights relevant vulnerability indicators that may represent hydro-geological, socioeconomic, institutional/cultural and ecological factors, and thus presents such indicators as useful tools to assess and reflect vulnerability and climate change impacts on environmental systems and ecosystems.

Table 1.3 A Methodologies adopted for the investigation and management of groundwater resources

Methodologies/ Approach	Objective	Model/Tool	Contaminant	Study area	Receptors	Reference
Investigation/ Numerical modelling (DRASTIC)	Intrinsic vulnerability of groundwater aquifer	DRASTIC model and GIS tools	Nitrate	Zhangye river basin in China	Coastal aquifer	Wen et al. 2008
Investigation/ Numerical modelling (SEAWAT CODE)	Predict saltwater intrusion into coastal aquifer	MODFLOW with SEAWAT CODE	Saltwater	Gulf coast of Alabama in USA	Coastal aquifer	Lin et al. 2009
Investigation/ Numerical modelling (MOCDENS3D)	How sea level rise and human activities will influence saltwater intrusion	MODFLOW implemented with hydrogeological parameters	Saltwater	Groundwater resources in Ravenna, Italy	Inland aquifer	Regione Emilia-Romagna 2005 & Euro Weather 2006
Investigation/ Numerical modelling (MOCDENS3D)	Estimate the level of contaminant in groundwater due to SLR and land subsidence	Density dependent groundwater model	Saltwater and Chloride.	Northern coast of Wadden sea in Netherland	Coastal aquifer	Louw & Oude Essink 2006
Investigation/ Complex distributed modelling & 3D modelling framework	To test the potential sea level rise and groundwater pumping on saltwater intrusion	USGS-3D model and solute transport simulator –SUTRA 2.1	Saltwater and Chlorine	Dutch coastal areas and Florida aquifer system	Coastal aquifers	Van Baaren et al. 2010 & Payne 2010
Management/ Desalination	Addressing water shortage due to salinity	3D numerical modelling, Piezometers and Loggers.	Saltwater	Central coast of New South Wales, Australia	Coastal aquifer	Anderson et al. 2005 &2009
Management/ Abstraction, Desalination and Recharge (ADR)	To control saltwater intrusion into groundwater aquifers	Optimization and Density-dependent finite element model	Saltwater	Madras aquifer in India, Biscayne aquifer in Florida USA, and Gaza aquifer in Palestine.	Groundwater aquifers	Abd-Elhamid and Javadi, 2011

Table 1.3B Indicators/Indices considered for the assessment of groundwater contamination (N.D. not defined)

Category	Objective	Factors Considered	Model / Scenarios used	Indicators/Indices	Aggregation Formula	Study area/Scale	Reference
Indicators for vulnerability assessment and mapping of groundwater in karst areas	Methodology for creating maps of intrinsic vulnerability of groundwater to human activities.	• Geophysical • Ecological • Hydrological • Meteorological	N.D	• Thickness of the soil • Hydraulic conductivity value • Porosity value; Soil type • Drainage density • Presence of karst • Slope of the surface • Physical properties of the soil • Vegetation type • Precipitation	N.D	Regional	Daly et al. 2002
Indicators of climate change impacts on groundwater	To compare the effects of potential climate change on groundwater recharge, storage and flow.	• Geophysical • Hydrogeological • Hydrological • Meteorological	Hydrogeological and Climate model. IPCC A2 and B2.	• Surface flow • Drainage flow • Base flow • Temperature • Precipitation • Evapotranspiration	N.D	Regional/ New Zealand and Denmark	Van Roosmalen et al. 2007
Indicators of climate change effects on groundwater recharge	Analyse the effects of climate change on groundwater	• Geophysical • Hydrological • Hydrogeological • Meteorological	Hydrological model	• Change in deposits of underground water (DSG) • Change in deposits of surface water (DSs). • Change in deposits in the vadose zone (DSv). • Changes in precipitation (P). • Evapotranspiration (ET). • Drainage flow (X). • Surface flow (O). • Infiltration (I).	DSG = R - G – W R = Net Recharge G = Net flow of W = Net extraction DSs= P-ET-O-I DSv= I-R-X	Regional/ Edward aquifer system in USA	Loáiciga, 2003.
Indicators of intrinsic vulnerability of aquifer	To determine the intrinsic vulnerability of aquifer using parametric SINTACS	• Geophysical • Hydrogeological • Chemical	N.D	• Groundwater depth (D). • Effective infiltration (I). • Vadose zone - lithological classes (N). • Type of soil (T). • Type of aquifer (A). • Hydraulic conductivity (C). • Topography (X).	$Iv = \Sigma P_{(1,7)} \cdot W_{(1,n)}$ Iv = index SINTACX of vulnerability $P_{(1,7)}$= score of each of the seven parameters used (S, I, N, T, A, C, X) $W_{(1,n)}$= weight Associated with each parameter	Local/ San Miguel de Allende, Mexico	Mahlknecht et al., 2006.
Indicators of vulnerability of coastal aquifers.	To determine the vulnerability of coastal aquifers due to rising sea coastal vulnerability index.	• Geophysical • Hydrogeological	N.D	• Rate of sea level rise. • Proximity to the coast. • Type of aquifer. • Hydraulic conductivity of soil. • Depth of groundwater below the sea level	N.D	Local/ Goksu delta in Turkey	Özyurt, 2007.

Category	Objective	Factors Considered	Model / Scenarios used	Indicators/Indices	Aggregation Formula	Study area/Scale	Reference
Indicators of climate change impacts on groundwater: Temperature, precipitation and Evapotranspiration	To provide information necessary to achieve sustainable balance between natural recharge and anthropogenic abstraction.	• Geophysical • Hydrological • Hydrogeological	N.D	• Change in flow of springs. • Fluctuations of the piezometric surface due to anthropogenic pressures. • Infiltration media through coefficients infiltration potential.	N.D	Regional /Campania, Italy	Ducci & Tranfaglia, 2005.
Indicators of climate change impacts on groundwater. We consider as forcing: precipitation (amount and intensity) and temperature.	To study the variation of the piezometric level of groundwater.	• Geophysical • Hydrological • Hydrogeological	N.D	• Permeability of soils. • Drainage from the waterways. • Changes in water level of the groundwater. • Infiltration effective. • Irrigation.	N.D	Local / plain Vercelli, Regional Piemonte, Italy	De Luca et al. 2005.
Indicators of vulnerability of aquifers to pollution.	To determine and map the vulnerability of aquifer pollution through the DRASTIC and Aquifer Vulnerability Index (AVI)	• Geophysical • Hydrogeological	N.D	• Depth of water table (D) • Reload net - infiltration (R) • Type of aquifer (A) • Type of soil (S) • Topographic slope (T) • Impact of the vadose zone (I) • Hydraulic conductivity (C) • Vertical hydraulic conductivity (Ks). • The thickness of the layers that are above the water table = (Hs).	$V_i = \Sigma^{7}{}_{i=1}(W_i$ □□$R_i)$ Vi = index (DRASTIC) Wi = weight indicator Ri = Score indicator Classes of vulnerability: Extremely high= ≥140, High= 120-140, Moderate= 100-120 Low= ≤ 100 $V_i = \Sigma^{n}{}_{s=1} H_s / K_s$ V_i = AVI index	Local / Rio Turbio Valley, in the central state of Guanajuato Mexico	Leal &Castillo, 2003
Indicators of vulnerability of aquifers to seawater intrusion.	To determine the vulnerability of the aquifer to the intrusion of seawater through the GALDIT index.	• Geophysical • Hydrogeological • Chemical	N.D	• Type of aquifer (w = 1). • Aquifer hydraulic conductivity (w = 3). • Height of the groundwater level to the sea level (w = 4). • Distance from the coast (w = 4). • Saline intrusion was expressed in the range of relationship- Cl / (HCO 3 -1 + CO 3 -2) in groundwater (w = 1). • Aquifer thickness (w = 2).	${}^{6}{}_{i=1} = (W_i \cdot R_i) / \Sigma^{6}{}_{i=1} W_i \Sigma^{6}{}_{i=1} =$ indice GALDIT W_i = weight of indicator R_i = importance of indicator Vulnerability classes: High ≥ 7.5, Moderate 5-7.5, Low ≤ 5	Local Northern coast Goa, India	Ferreira, 2005.

1.4 PROPOSED METHOD TO PROTECT AND MANAGE GROUNDWATER RESOURCES

This thesis seeks to offer a spatially resolved regional risk assessment (RRA) method useful to analyse impacts on coastal systems from different sources that vary worldwide and to identify dependent ecosystems that will be more prone to the consequences of these impacts. The methodology was developed and implemented in compliance with the research activities of the Euro-Mediterranean Centre for Climate Change (CMCC), to evaluate potential climate change and anthropogenic effects on the Esino River coastal aquifer and related ecosystems, considering different future climate change scenarios with reference to seasons. Accordingly, the thesis is intended to be an aid for national and regional authorities in examining the possible consequences associated with environmental issues and prioritizing possible adaptation measures. Moreover, the methodology can represent valid support for the different stakeholders involved in the implementation of an Integrated Coastal Zone Management (ICZM). Traditionally, the regional risk assessment approach aims at providing a quantitative and systematic approach to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990). This approach is defined as a risk assessment procedure, which considers the presence of multiple habitats and sources releasing multiple stressors that could affect diverse endpoints (Landis, 2005).

The spatially resolved methodology is part of a more comprehensive framework for "impact and risk assessment" in coastal areas at the regional scale. The framework integrates relevant tools and methodologies for the identification of potential impacts and the assessment of bio-physical and socio-economic vulnerability, to estimate relative risks in the considered coastal region, and is composed of 3 main phases: the *Scenarios construction phase*, which is aimed at the definition of future scenarios for the examined hazards and case study area at the regional scale; the *Integrated impact and risk assessment phase*, which is aimed at the prioritization of impacts, targets, and affected areas at the regional scale; and the *Risk and impact management phase*, which is devoted to support adaptation strategies for the reduction of the risks and impacts in accordance to ICZM principles. According to this framework, the main outputs of the methodology are GIS-based maps that include exposure maps, representing the exposure to changes that a system might functions and vulnerability maps, representing the spatial distribution of environmental and socio-economic vulnerability features. These maps allow the visualization and prioritization of impact areas and vulnerable coastal receptors/targets, the identification of more sensitive areas in the coastal territory, and the location of more suitable areas for human settlements, infrastructure and economic activities. Moreover, they allow an easy and flexible visualization of vulnerabilities, and risks for stakeholders and decision makers, supporting the implementation of the ICZM. For this purpose, the spatially resolved RRA method is implemented with the GIS-based DEcision support SYstem for COastal climate change impacts assessment (DESYCO) tool developed within the CMCC research consortium (www.cmcc.it/data-models/models/desyco). DESYCO is open source software that can manage different input datasets (e.g. raster or shape files) of climate change hazard scenarios based on global/sub continental scales, regional climate projections (e.g. high resolution hydrodynamic, hydrological and biogeochemical simulations), and site-specific physical, ecological and socioeconomic features of the considered region (e.g. coastal topography, geomorphology, presence and distribution of vegetation cover, location of artificial protection). The basis of the system is represented by the relative risk model that employs Multi-Criteria Decision Analysis (MCDA) techniques in order to identify areas exposed to climate related hazards, estimate susceptible exposure units and relative risks in the considered region, and provide a final evaluation of the potential damages associated to the analysed receptors. Graphical user interfaces guide the user in a step-by-step application of DESYCO and the analysis of its relevant outputs (i.e. GIS-based exposure, susceptibility, risk and damage maps). This makes the spatially resolved methodology suitable not only to analyse the relative effects of climatic trends for coastal groundwater resources but also to identify dependent ecosystems that will be severely prone to consequent risks (Iyalomhe et al., 2013 forthcoming).

1.5 THESIS AIMS AND OBJECTIVES

This thesis aspires to achieve the following specific research aims: First, the application of a relative risk model to evaluate regional climate-related impacts on coastal groundwater aquifers and prioritize consequent risks on dependent ecosystems. This research is intended to support the efforts of concerned stakeholders that are involved in the protection and management of groundwater resources, and the implementation of two European Union policy instruments: the Water Framework Directive (WFD 2000/60/EC) and the Groundwater Directive (2006/118/EC). Second, the thesis proposes and applies concepts of communities of practice as a basis for understanding the social dynamics that exist between climate scientists/experts and policy-makers/stakeholders in climate change adaptation projects. Such research will facilitate and sustain relations and foster joint production of contextual knowledge needed for climate change adaptation. The specific objectives are:

1. Examine current methodologies applied with decision support systems to study coastal systems' issues caused by climate change at the European and international levels;
2. Identify and define relevant indicators and indices for the assessment of climate-related impacts and the vulnerability of coastal ecosystems;
3. Adapt the regional risk assessment (RRA) approach to coastal ecosystems impacts and risks caused by climate change and anthropogenic pressures;

4. Apply the adapted RRA approach (i.e. spatially-resolved RRA methodology) to assess and characterize climate change impacts and risks on a coastal aquifer in the lower Esino River valley;
5. Investigate the efficacy of this methodology to respond to policy and decision makers' needs, and guide the definition of regional adaptation measures; and
6. Improve the conceptual understanding of social dynamics in the climate change adaptation arena.

1.6 THESIS OUTLINES

The outline corresponds to the specific undertakings of the thesis in regard to the defined objectives in chapter one, and thus represents the research work discussed in the six chapters: one introductory chapter, one theoretical chapter, one methodological chapter, two application chapters, and a conclusions chapter. Apart from the introduction, methodological and conclusions chapters, other chapters are researched in the form of individual peer-reviewed articles. The thesis is thus organized as briefly described below:

Chapter 2 explores the application of techniques and tools devoted to study coastal systems and related ecosystems issues. In particular, an analysis of existing decision support systems (DSS) related methodologies focusing on climate change impacts on coastal systems and related ecosystems were conducted by surveying the open literature. Consequently, twenty DSSs were selected and analysed according to their specific objectives and basic functionalities. In particular, this analysis considered a set of criteria (i.e. general technical, specific technical and applicability), to highlight the DSSs' functionalities necessary for the implementation of regulatory frameworks devoted to support the management of climate change related issues. By examining the major features and applicability of each DSS, this research can help the reader or potential users in the selection of DSS tailored to their specific application needs. In addition, the chapter presents a review of current methodologies and relevant indicators and indices devoted to support the study of coastal ecosystems' vulnerability to climate change and anthropogenic stressors.

Chapter 3 discusses the development and adaptation of the proposed methodology based on a regional risk assessment (RRA) approach that aims to provide a systematic way to estimate and compare the impacts of environmental problems that can affect large geographical areas (Hunsaker et al., 1990). The RRA is considered as a risk assessment procedure, which takes into account the presence of multiple habitats, diverse sources contributing to a multiplicity of stressors that affect various endpoints as well as the characteristics of the landscape that affect the risk estimate (Landis, 2005). Therefore, the proposed methodology, which is based on the Sources-Pathway-Receptor-Consequences (SPRC) approach (Ministry for the Environment of New Zealand, 2008), is characterized by the regional scale of analysis, which implies the assessment and integration of a huge amount of input data and the use of Multi Criteria Decision Analysis (MCDA) techniques, to estimate relative risks in the considered region, compare different impacts and stressors, and rank targets and exposure units at risk. The methodology is based on the preliminary definition of a framework for the integrated analysis of climate change impacts and risks for groundwater at the regional scale. The framework also represents the main relationships among natural and anthropogenic forcing, generated stressors and the consequent environmental and socio-economic impacts. It is thus useful to analyze relevant impacts on surface and sub-surface waters and to identify the multiple relationships with impacts on socio-economic systems and biodiversity. The RRA approach and the defined framework allow integrating all relevant environmental components and their complex interactions through an integrated risk analysis procedure that involves hazard characterization and vulnerability assessment.

Chapter 4 presents the spatially resolved regional risk assessment (RRA) methodology development and its application within the European Life + SALT (i.e. Sustainable mAnagement of the Esino River basin to prevent saline intrusion in the coastaL aquifer in consideration of climaTe change) project. The project was aimed at identifying climate change-related threats to the Esino coastal aquifer and its dependent ecosystems (i.e. lakes, rivers, agricultural areas, forests and semi-natural environments), and at ranking targets and areas potentially at risk. Relevant impacts (i.e. Groundwater Level Variations and Saltwater Intrusion) were systematically and quantitatively analysed through the spatial characterization of hazard scenarios and the assessment of exposure, susceptibility, and risk and damage. The spatially resolved methodology employed three different future climate change scenarios characterized by different precipitation amounts (i.e. average, dry and wet years) with reference to four different seasons (i.e. winter, spring, autumn and summer). Scenarios were constructed through the application of a chain of climate, hydrology, hydraulic and groundwater systems models, for the 2070-2100 timeframe and according to the IPCC SRES A1B emission scenario. The main aim of the methodology is to provide indicators of potential risks, responding to water managers' needs for the implementation of the key principles of the Water Framework Directive and Groundwater Directive. The results indicate that in the future scenarios, potential climate change will exert slight difference in impacts and risks for the case study area. More specifically, groundwater level variation impacts in the summer will exert limited direct effects on specific agricultural areas and forests and semi-natural systems located along the coastline and superficial water bodies. Moreover, the saltwater intrusion impacts will be restricted to the coastal strip, and thus subject to limited effects on the Esino coastal aquifer in the future seasons and few indirect consequences for dependent ecosystems.

Chapter 5 proposes and applies a new approach to improve the conceptual understanding of the science-policy interface that exists within the climate change adaptation arena. It considers the communities of practice theory in a new way, by examining two model cases (i.e. Red River Delta in

Vietnam and SALT in Italy) to highlight aspects of potential opportunities for the theory and the disagreements between the theory and cases. It also aims to understand how a successful science-policy interface in climate change adaptation projects could be envisioned as a community of practice. The assumption is that the social contexts, in which these projects often exist, could be established by the concept of 'communities of practice,' which defines activities in a social and historical context that gives structure to the engagement of participants. Model cases were compiled from open-ended surveys and interactive research experience and observation, and were inductively reflected on **vis-**à-**vis** communities of practice. The cases revealed challenges as well as potential opportunities for communities of practice. They exist within a middle space (social context) that could facilitate personal and professional relationships and promote formal and informal interactions, needed to negotiate different expertise and narrow apparent boundaries. I conclude that vigorous and dynamic communities of practice promise to nurture the social context in which participants in adaptation projects are potentially engaged, and thus provide provisional support to the science-policy interface.

Chapter 6 presents the conclusions and possible future investigations and recommendations.

1.7 REFERENCE

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CHAPTER 2

Analysis of GIS-Based Decision Support Systems Addressing Climate Change Impacts on Coastal Waters and Related Inland Watersheds

F. Iyalomhe, J. Rizzi, S. Torresan, V. Gallina, A. Critto and A. Marcomini (2013). Inventory of GIS-Based Decision Support Systems Addressing Climate Change Impacts on Coastal Waters and Related Inland Watersheds, Climate Change - Realities, Impacts Over Ice Cap, Sea Level and Risks, Prof. Bharat Raj Singh (Ed.), ISBN: 978-953-51-0934-1, InTech, DOI: 10.5772/51999.

Abstract

Climate change is increasingly becoming a crucial subject in the global change debate and discourse; its effects on human environments particularly coastal zones and inland water systems are now a huge challenge to environmental resource managers and decision makers. International and regional regulatory frameworks have been established to guide the implementation of interdisciplinary methodologies, useful to analyse water-related systems issues and support the definition of management strategies against the effects of climate change. As a response to these concerns, several Decision Support Systems (DSS) have been developed and applied to address climate change through Geographical Information Systems (GIS) linking the DSS objectives with specific functionalities leading to key outcomes, and aspects of the decision making process involving coastal and inland waters. An analysis of existing DSS focusing on climate change impacts on coastal and related inland waters were conducted by surveying the open literature. Twenty DSS were identified and are presented here according to their general and specific objectives. A set of technical criteria was used to describe the considered DSS and evaluate their actual applicability.

2.1. INTRODUCTION

Decision Support Systems (DSSs) are computer-based software that can assist decision makers in their decision process, supporting rather than replacing their judgment, and at length, improving effectiveness over efficiency (Janssen, 1992). DSSs have been developed and used to address complex decision-based problems in varying fields of research. For instance, in environmental resource management, DSS are generally classified into two main categories: Spatial Decision Support Systems (SDSS) and Environmental Decision Supports Systems (EDSS) (Matthies et al., 2007; Uran and Janssen, 2003; Poch et al., 2004). SDSS provide the necessary platform for decision makers to analyse geographical information in a flexible manner, while EDSS integrate the relevant environmental models, database and assessment tools – coupled within a Graphic User Interface (GUI) – for functionality within a Geographical Information System (GIS) (Janssen, 1992; Fabbri, 1998; Uran and Janssen, 2003; Poch et al., 2004). In some detail, GIS is a set of computer tools that can capture, manipulate, process and display spatial or geo-referenced data (ESRI, 1992) in which the enhancement of spatial data integration, analysis and visualization can be conducted (Nobre and Ferreira 2009; Mathies et al., 2007). These functionalities make GIS-tools useful for efficient development and effective implementation of DSS within the management process. For this purpose they are used either as data managers (i.e. as a spatial geo-database tool) or as an end in itself i.e. media to communicate information to decision makers (Nobre and Ferriera, 2009).

At present the increasing trends of industrialisation, urbanisation and population growth has not only resulted in numerous environmental problems but has increased the complexity in terms of uncertainty and multiplicity of scales. Accordingly, there is a consensus on the consideration of several perspectives in order to tackle environmental problems, particularly, climate change related impacts in coastal zones that are characterised by the dynamics and interactions of socio-economic and bio-geophysical phenomena. There is the need to develop and apply relevant tools and techniques capable of processing not only the numerical aspects of these problems but also knowledge from experts, to assure stakeholder participation which is essential in the decision making process (Poch et al., 2004) and to guarantee the overall effectiveness of assessment and management of coastal environments – including related inland watersheds (i.e. surface and groundwater affected by, and affecting, coastal waters).

The scientific community projected that climate change would further exacerbate environmental problems due to natural and anthropogenic impacts – with specific emphasis in coastal areas (IPCC, 2007). This, however, depends on global and regional policy measures especially in sectors such as energy, economy and agriculture, which seem to be a major threat to global sustainable development. As a response to this, mitigation and adaptation measures are already identified through intense research activities, yet these may not limit the projected effects of climate change over the next few decades. On the one hand, there is the influence of socio-economic development and environmental response, while on the other, there is the significant uncertainty still associated with present climatic predictive models. Thus, model inputs need to take into account scenarios highly affected by present and future policy measures in order to further reduce uncertainty in their predictions and thereby guarantee robust adaptation strategies.

In addition, climate change effects have been linked to the increase in global average temperature according to the IPCC emission scenarios (Nakićenović & Swart, 2000). Resulting ocean thermal expansion is expected to generate significant impacts via sea level rise, seawater intrusion into coastal aquifers, enhanced coastal erosion and storm surge flooding, while increasing population in coastal cities, especially megacities on islands and deltas, further aggravates major impacts of climate change on marine coastal regions. The latter include transitional environments such as estuaries, lagoons, low lying lands, lakes, which are particularly vulnerable because of their geographical location and intensive socio-economic activities (Nicholls and Cazenave, 2010; Jiang and Hardee, 2010).

Accordingly, several environmental resource regulations have already included the need to assess and manage negative impacts derived from climate change through their implementation. For instance, the European Commission approved the Green and White papers (EC, 2000; EC, 2002), the Water Framework Directive (WFD, 2000/60/EC), which represent an integrated and sound approach for the protection and management of water-related resources in both inland and coastal zones and the protocol for Integrated Coastal Zone Management (ICZM), which promote the integrated management of coastal areas in relation to local, regional, national and international goals. Moreover, the principles of Integrated Water Resources Management (IWRM) aimed to address typical water quality and quantity concerns with the optimisation of water management and sustainability in collaboration with WFD policy declarations (EC, 2003). Likewise, relevant national legislation, the Shoreline Management Planning (SMP) in the United Kingdom, Hazard Emergency Management (HEM) in the United States and Groundwater Resources Management (GRM) in Bangladesh and India were ratified and further endorse the assessment and management of coastal communities in relation to climate change impacts. Within this context, the development of innovative tools is needed to implement regulatory frameworks and the decision making process required to cope with climate related impacts and risks. To this aim, DSS are advocated as one of the principal tools for the described purposes.

This work will attempt to examine GIS-based DSS resulting from an open literature survey. It will highlight major features and applicability of each DSS in order to help the reader in the selection of DSS tailored for his specific application needs.

2.2 DESCRIPTION OF THE SELECTED DECISION SUPPORT SYSTEMS

The literature survey led to the twenty DSSs designed to support the decision-making process related to climate change and environmental issues in coastal environments, including inland watersheds. The DSSs relevant information is summarised in Table 1 with the indication of the developer, development years, and literature reference; to provide a description of the major features and an evaluation of the applicability of the 20 examined DSS. This work adopted a set of criteria reported in Table 2 and grouped them within three different categories: general technical criteria, specific technical criteria, and availability and applicability criteria. The general technical criteria underline relevant general features related to each DSS, which include: the target coastal regions and ecosystems domain; the regulatory frameworks and specific legislations supported by each DSS; the considered climate change impacts and related scenarios, as well as the objectives of the examined systems. The specific technical aspects include the main functionalities, analytical methodologies and inference engine (i.e. structural elements) of the systems. A final set of criteria concerned applicability, i.e. scale and study areas, flexibility, status and availability of the examined systems. In the following sections the identified DSS, listed in Table 1, will be presented according to these criteria.

2.2.1 General technical criteria

As far as the application domain, the considered DSS focus on coastal zones and related ecosystems (e.g. lagoons, groundwater, river basins, estuaries, and lakes), specifically thirteen DSS are on coastal zones, seven concern coastal associated ecosystems and four focuses on both (Table 3).

As far as regulatory frameworks (i.e. ICZM, WFD, and IWRM) and national legislations are concerned, the examined DSS reflect the assessment and management aspects of the related decision making process. Within the coastal, marine and river basin environments, the assessment phase of these frameworks consists of the analysis of environmental, social, economic and regulatory conditions, while the management phase looks at the definition and implementation of management plans. Accordingly, support is provided by each DSS to the implementation of one or two frameworks in the assessment and/or management phase in relation to specific objectives and application domain. Specifically, the investigated DSSs can provide the evaluation of ecosystem pressures, the assessment of climate change hazards, vulnerability and risks, the development and analysis of relevant policies, and the definition and evaluation of different management options. Eight out of the twenty examined DSSs provide support for the ICZM implementation through an integrated assessment involving regional climatic, ecological and socio-economic aspects (Table 3, second column). In regard to the WFD (i.e. six DSS) and IWRM (i.e. seven DSS), the main focus is on the assessment of environmental or ecological status of coastal regions and related ecosystems and on the consideration of anthropogenic impacts and risks on coastal resources. These two groups of DSS consider also the river basins management via evaluation of adaptation options, which is essential for the management phase of the WFD and IWRM implementation. Particularly interesting are the approaches adopted by three DSS: CLIME, STREAM and COSMO. CLIME supports both the assessment and management phases of WFD through the analysis of present and future climate change impacts on ecosystems and the socio-economic influence on water quality of the European lakes. STREAM evaluates climate change and land use effects on the hydrology of a specific river basin, in order to support the management phase of IWRM and WFD via the identification of water resources management measures. Lastly, COSMO provides support for the ICZM through the identification and evaluation of feasible management strategies for climate change and anthropogenic impacts relevant for coastal areas. Moreover, RegIS, Coastal Simulator, CVAT and GVT specifically support the implementation of national legislation through the consideration of socio-economic and technological issues relevant for identifying suitable mitigation actions. For this purpose, these DSSs promote the involvement of stakeholders through participatory processes.

The main objective of the examined DSS is the analysis of vulnerability, impacts and risks, and the identification and evaluation of related management options, in order to guarantee robust decisions required for sustainable management of coastal and inland water resources. Specifically, the objectives of the examined DSS are concerned with three major issues: (1) the assessment of vulnerability to natural hazards and climate change (four DSS: CVAT, GVT, SimLUCIA, TaiWAP); (2) the evaluation of present and potential climate change impacts and risks on coastal zones and linked ecosystems, in order to predict how coastal regions will respond to climate change (nine DSS); (3) the evaluation or analysis of management options for the optimal utilisation of coastal resources and ecosystems through the identification of feasible measures and adequate coordination of all relevant users/stakeholders (seven DSS: WADBOS, COSMO CORAL, DITTY, ELBE, MODSIM, RAMCO).

According to the climate change impacts considered by the examined DSS, the review highlights that fifteen out of the 20 DSS applications regard the assessment of climate change impacts and related risks (CC-DSS). These DSS consider climate change impacts relative to sea level rise, coastal erosion, and storm surge flooding and water quality. In particular, DESYCO also consider relative sea level rise in coastal regions where there are records of land subsidence, whereas KRIM and CVAT assess impacts related to extreme events and natural hazards (e.g. typhoon, cyclone, etc.) respectively. Moreover, GVT is specifically devoted to groundwater quality variations.

The relevant climate change related scenarios considered by the examined DSSs refer to emissions of greenhouse gases, temperature increase, sea level rise and occurrence of extreme events. In addition, CVAT used previous observations as baseline scenarios for the assessment of natural hazards, while RegIS considered scenarios related to coastal and river flooding along with socio-economic scenarios in order to estimate their potential feedback on climate change impacts. Although most of these CC-DSS applications used sea level rise scenarios, only DIVA used global sea level rise scenarios to estimate related impacts like coastal erosion and storm surge flooding. KRIM is the only DSS considering extreme events scenarios in its analysis to support the development of robust coastal management strategies.

2.2.2 Specific technical criteria

The criteria related to the specific technical aspects are reported in Table 4. As far as the functionalities are concerned (Table 4, first column), the ones implemented by DESYCO, COSMO, SimCLIM, KRIM and RegIS include the identification and prioritisation of impacts, targets and areas at risk from climate change, sectoral evaluation of impacts or integrated assessment approach, and vulnerability evaluation and problem characterisation, in order to differentiate effectively and quantify impacts and risks at the regional scale. Moreover, they also support the definition and evaluation of management options through GIS-based spatial analysis of climate change related impacts. Other DSSs, i.e. DIVA, SimCLIM, DESYCO and KRIM, implement scenarios import and generation, environmental status evaluation, impacts and vulnerability analysis and evaluation of adaptation strategies to adequately achieve a sustainable state of coastal resources and ecosystems.

In order to support effectively the assessment and management of groundwater resources, GVT and DESYCO estimate indicators in assessing impacts, vulnerability and risks to evaluate groundwater quality and coastal environmental quality, respectively. Similarly, STREAM, ELBE, RAMCO and DITTY employ environmental status evaluation, protection measures evaluation, and spatial analysis to support the management aspects of coastal ecosystems. Moreover, CLIME and CORAL specifically support the assessment and management of lakes and coral reefs via the adoption of management strategies and the evaluation and identification of pressures from climatic variables.

In particular, five out of the 20 examined DSSs (i.e. CVAT, GVT, Coastal Simulator, SimLUCIA and RegIS) consider hazards identification, impacts and vulnerability evaluation, mitigation/ management options identification, and evaluation and sectoral evaluation to achieve a comprehensive and integrated analysis of coastal issues at the local or regional scale. Among all considered DSSs, RegIS proved to be the most stakeholders oriented.

The second column of table 4 shows the methodologies adopted by each DSS. Seventeen out of 20 examined DSS consider scenarios analysis to enable coastal managers, decision makers and stakeholders to anticipate and visualise coastal problems in the foreseeable future, and to better understand which future scenario is most suitable for consideration in the evaluation process. A useful methodology is represented by the Multi-Criteria Decision Analysis (MCDA) technique that is considered by five DSS (i.e. COSMO, DESYCO, DITTY, GVT and WADBOS), to compare, select and rank multiple alternatives that involve several attributes based on several different criteria. Moreover, DITTY and RegIS also consider the Drivers-Pressures-State-Impacts-Responses (DPSIR) approach as a causal framework to describe the interactions between the coastal system, society and ecosystems and to carry out an integrated assessment with the aim to protect the coastal environment, guarantee its sustainable use, and conserve its biodiversity in accordance to the Convention on Biodiversity (2003). An ecosystem assessment was adopted by ten DSSs (i.e. CORAL, COSMO, Coastal simulator, DIVA, RegIS, KRIM, RAMCO, SimLUCIA, SimCLIM, and DESYCO), to support the analysis of the studied region through the representation of relevant processes and their feedbacks. Furthermore KRIM, IWRM, COSMO, SimCLIM and Coastal Simulator and DESYCO employ the risk analysis approach for impacts and vulnerability evaluation and also for general environmental status evaluation. A more detailed approach to risk analysis, through the regional risk assessment methodology (RRA), was adopted by DESYCO, Coastal Simulator and RegIS with huge emphasis on the local or regional scales. Finally, CLIME and SimLUCIA consider the Bayesian Probability Network to highlight the causal relationship between ecosystems (e.g. lakes) and climate change effects.

With regard to the structure of examined DSSs (Table 4, third column), most of them employ analytical models useful to highlight the basic features and natural processes of the examined territory, such as the landscape and ecological models used by the WADBOS, the environmental model employed by RAMCO, the geomorphological model used within KRIM and the flood meta-model which interface other models considered by the RegIS. Moreover, the majority of these DSS utilise numerical models necessary to simulate relevant circulation and geomorphological processes that may influence climate change and related risks. DSS like CLIME, DESYCO, CVAT and TaiWAP adopt models useful to represent specific climatic processes (e.g. hydrological cycle and fate of sediment). More importantly, eleven (i.e. WADBOS, SimLUCIA, RAMCO, MODSIM, GVT, ELBE, DIVA, CORAL, DITTY, RegIS and SimCLIM) out of the twenty examined DSS consider relevant socioeconomic models outputs in their analysis to critically support the integrated assessment of coastal zones. Finally, the majority of these DSS consider integrated assessment models in order to emphasise the basic relationship among different categories of environmental processes such as physical, morphological, chemical, ecological and socio-economic – and to provide inclusive information about the environmental and socioeconomic processes.

As far as the software interfaces are concerned, very few of the examined DSS are applied through web-based interfaces, in spite of the fact that web-based facilities enhance easy access to information within a large network of users. Furthermore, all the reviewed DSSs consider GIS tools as basic media to express their results or outputs in order to provide fast and intuitive results representation to non-experts (i.e. decision makers and stakeholders) and empower them for robust decisions. In addition to maps, the outputs produced by each DSS are also graphs, charts, and statistical tables.

2.2.3 Applicability criteria

Table 5 shows the implementation of the criteria concerning applicability to the examined DSSs. Applicability includes three aspects: scale/study areas, flexibility and status/availability (Table 2). The spatial scales considered were five: global, supranational, national, regional, and local, in order of decreasing size. The study areas are those reported in the literature cited in Table 1. The flexibility derives from the capability of a given DSS to include new modules and models in its structure, thus new input parameters, and the suitability to be used for regionally different case studies. In order to visualize the estimation of the overall flexibility of a system, highly flexible/flexible/moderately-to-no flexible were indicated as +++/++/+. Status and availability refer to different extent of development (e.g. research prototype, commercial software) and public accessibility/last updated version, respectively.

As far as the scale of application is concerned, all the examined DSS, except DIVA, have been applied only at the local and regional scales because they were developed for a specific geographical context. Moreover, five out of the 20 examined DSS (i.e. CLIME, CORAL, DITTY, DIVA and STREAM) considered global, supranational, national, regional and local scales during their implementation.

Five of the reported DSSs are highly flexible systems because they are used to address several impacts related to different case studies. Although DIVA can be applied to any coastal area around the world, it is sometimes not considered a highly flexible tool in terms of structural modification due to its inability to change its default-integrated dataset. Finally, ELBE and WADBOS are identified as moderately-to-no flexible systems because their structure and functionalities were based on the specific needs of particular river basins.

The applicability of DSSs reflects their ability to be implemented in several contexts (i.e. case study areas and structural modification), for example to include new models and functionalities ensuring common approaches to decision making and the production of comparable results (Agostini et al., 2009).

Finally, concerning the availability and the status of the development, Table 5 shows that nine DSSs are available to the public, three are available with a restricted access (i.e. only to stakeholders or to the developers), one is a commercial software (i.e. COSMO) and seven are not available to the public. Sometimes the restriction of the access is due to the fact that results require special skill for their interpretation, so the public can use them only with the support of the developer team. Among the DSSs, only 11 were developed/updated during the last 5 years, and 4 over the previous five years (for a total of 15 during the last 10 years) with the remaining five DSS showing the last version dating back to the ‘90s.

The overall content of Table 5, together with the main features of each DSS reported in Tables 3 and 4, allow the reader to undertake a screening evaluation of available DSS in relation to the specific impacts from climate change to be addressed.

2.3 CONCLUSIONS

This work should be regarded as a snapshot of the present DSSs devoted to climate change related issues in the coastal environments. Besides, it describes and evaluates the main features of these DSSs for the assessment and management of climate change impacts on coastal area and related inland watersheds. Accordingly, the analysis highlighted the relevance of developing climate change impact assessment and management at the regional scale (i.e. subnational and local scale), according to the requirements of policy and regulatory frameworks and to the methodological and technical features of the described DSSs. Without a doubt, most of the available DSSs show a regional to local applicability with a moderate to high flexibility, and focus mainly on the analysis of specific individual climate change impacts and affected sectors (15 out of the 20 examined DSS). Except for few DSSs, such as DESYCO that has proved to support effectively relevant stakeholders in the implementation of key regulatory frameworks and regional management of diverse potential climate change impacts and associated risks.

DESYCO provides functionalities useful to support the assessment phases of several environmental regulatory frameworks (e.g. ICZM and WFD and Groundwater Directive), through integrated regional risk assessment approach that is also an ecosystem approach to the characterization and ranking of regional risks due to climate change and anthropogenic pressures. Moreover, DESYCO includes relevant techniques for the consideration of different climate change related impacts on coastal environments and related ecosystems, according to input from integrated assessment model and tools. This supports the understanding of dynamic and complex nature of coastal impacts and consequent risks on related ecosystems, through adequate identification and description of results from impacts and risks analysis. However, DESYCO does proved to be non-stakeholders tool, i.e. stakeholders' participation in its development and implementation until date is very low, even though it considers data from diverse sources and can be applied on different regions and case study areas. Still, DESYCO proves to be an effective tool for ecosystem approach to climate change impacts assessment and management at the regional scale and thus the reason for its application within this PhD analyses.

A further and comprehensive evaluation should be based on comparative application in selected and relevant case studies, in order to evaluate the DSS technical performance, especially in relation to datasets availability, that often represents the real limiting factor. Moreover, sensitivity and uncertainty analyses will provide further evidence of the reliability of the investigated DSS.

Finally, it is important to remark the need to involve the end users and relevant stakeholders since the initial steps of the development process of these tools, in order to satisfy their actual requirements, especially in the perspective of providing useful climate services, and to avoid the quite often and frustrating situation where time and resource demanding DSS are not used beyond scientific testing exercises. Also DSSs' further developments should aim at the adoption of ecosystem approaches considering the complex dynamics and interactions between coastal systems and other systems closely related to them (e.g. coastal aquifers, surface waters, river basins, estuaries), and at the adoption of multi-risk approaches in order to consider the interaction among different climate change impacts that affect the considered region.

Table 1. List of existing DSS on coastal waters and related inland watersheds

Name	Developer	Year of Development	Reference Sources
CLIME: Climate and Lake Impacts decision support system	Helsinki University of Technology, Finland	1998-2003	Jolma et al. 2010 http://clime.tkk.fi
CORAL: Coastal Management Decision Support Modelling for Coral Reef Ecosystem	Within a World Bank funded Project: LA3EU	1994-1995	Westmacott & Rijsberman 1995
COSMO: Coastal zone Simulation MOdel	Coastal Zone Management Centre, Hague	1992	Feenstra et al. 1998
Coastal Simulator decision support system.	Tyndall Centre for Climate Change Research, UK.	2000-2009	Nicholls et al. 2009
CVAT: Community Vulnerability Assessment Tool	National Oceanic and Atmospheric Administration, US.	1999	Flax et al. 2002 www.csc.noaa.gov/products/nchaz/startup.htm
DESYCO: Decision Support SYstem for COastal climate change impact assessment	Euro-Mediterranean Centre for Climate Change, (CMCC) Italy.	2005-2010	Torresan et al. 2010
DITTY: Information technology tool for the management of Southern European lagoons	Within the European region project: DITTY	2002- 2005	Agnetis et al. 2006
DIVA: Dynamic Interactive Vulnerability Assessment	Potsdam Institute for Climate Impact Research, Germany	2003-2004	Hinkel & Klein 2009 http://www.dinas-coast.net.
ELBE: Elbe river basin Decision Support System	Research Institute of Knowledge System- RIKS, Netherland	2000-2006	BfG, 2003 www.riks.nl/projects/Elbe-DSS
GVT:Groundwater Vulnerability Tool	University of Thrace and Water Resource Management Authority, Greece.	2003-2004	Gemitzi et al. 2006
IWRM: Integrated Water Resources Management Decision Support System	Institute of Water Modelling, Bangladesh	2002-2010	Zaman, et al. 2009 www.iwmbd.org
KRIM decision support system	Within the KRIM Project in Germany.	2001-2004	Schirmer et al. 2003 www.krim.uni-bremen.de
MODSIM decision support systems	Labadie of Colorado State University, US	1970	Salewicz & Nakayama 2004 and Labadie 2006 www.modsim.engr.colostate.edu
RegIS-Regional Impact Simulator	Cranfield University, UK	2003-2010	Holman et al. 2008 http://www.cranfield.ac.uk/sas/naturalresources/research/projects/regis2.html
RAMCO: Rapid Assessment Module Coastal Zone Management	Research Institute of Knowledge System- RIKS, Netherland	1996-1999	de Kok et al. 2001 http://www.riks.nl/projects/RAMCO
SimLUCIA: Simulator model for St LUCIA	Research Institute of Knowledge System- RIKS within the UNEP Project, Netherland	1988-1996	Engelen et al., 1995 http://www.riks.nl/projects/SimLUCIA
SimCLIM: Simulator model System for Climate Change Impacts and Adaptation	University of Waikato and CLIMsystem limited, New Zealand.	2005	Warrick, 2009 www.climsystems.com
STREAM: Spatial Tools for River Basins and Environment and Analysis of Management Options	Vrije Universiteit Amsterdam and Coastal Zone Management Centre, Hague	1999	Aerts et al. 1999 http://www.geo.vu.nl/users/ivmstream/
TaiWAP: Taiwan Water Resources Assessment Program to Climate Change	National Taiwan University, Taiwan	2008	Liu et al. 2009
WADBOS: decision support systems	Research Institute of Knowledge System- RIKS, Netherland	1996-2002	van Buuren et al. 2002 www.riks.nl/projects/WADBOS

Table 2. List of criteria used for the description of existing DSS

Categories	Criteria
General technical criteria	• Coping with regulatory framework. This indicates the particular legislation or policy, the DSS refers to and which phase of the decision-making process is supported at the National, Regional and Local level (e.g., EU WFD, ICZM, IWRM, SMP, GRM, and HEM). • Study/ field of application area. The coastal zones where this DSS has been applied and tested (e.g., coastal zone, lakes, river basin, lagoon, groundwater aquifer etc.) • Objective. It specifies the main aims of the DSS. • Climate change impacts. This refers to relevant impacts due to climate change on the system (e.g., sea-level rise, coastal flooding, erosion, water quality). • Climate Change Scenarios. The kind of scenarios considered by the DSS, which are relevant to the system analysis and connected to climate change (e.g., emission, sea level rise, climatic scenarios).
Specific technical criteria	• Functionalities. These indicate relevant functionalities (key outcomes) of the system useful to the decision process: environmental status evaluation, scenarios import (climate change and socio-economic scenarios) and analysis, measure identification and/or evaluation, relevant pressure identification and indicators production. • Methodological tools/ (analytical tools). These indicate the methodologies included in the system such as risks analysis, scenarios construction and/or analysis, integrated vulnerability analysis, Multi-Criteria Decision Analysis (MCDA), socio-economic analysis, uncertainty analysis, ecosystem-based approach etc. • Structural elements. The three major components of the DSS: dataset (i.e., the typology of data), models (e.g., economic, ecological, hydrological and morphological), interface (i.e., addressing if it's user-friendly and desktop or web-based).
Availability and applicability	• Scale and area of application. This specifies the spatiality of the system (e.g., local, regional, national, supra-national and global) within the case study areas. • Flexibility. The characteristics of the system to be flexible, in terms of change of input parameters, additional modules or models and functionalities. It is also linked to the fact that it can be apply on different coastal regions or case study areas. • Status and Availability. This specifies if the system is under development or already developed and ready for use, and if it is restricted to the developer and case study areas only or the public can access it too and the website where information about the DSS can be found.

Table 3: List of the examined DSSs according to the general technical criteria (ND: Not Defined)

Name	Application domain	Regulatory Framework of reference	Objective	Climate change impacts addressed	Climate change scenarios generating impacts
CLIME	• Lakes.	WFD for environmental assessment.	To explore the potential impacts of climate change on European lakes dynamics linked coast.	• Water quality.	• Emission scenarios. • Temperature scenarios.
CORAL	• Coral reef	IWRM and ICZM both for environmental assessment and management.	Sustainable management of coastal ecosystems in particular, coral reefs.	• ND	• ND
COSMO	• Coastal zones.	ICZM for environmental management.	To evaluate coastal management options considering anthropic (human) forcing and climate change impacts.	• Sea-level rise.	• Sea-level rise scenarios.
Coastal Simulator	• Coastal zones.	National legislation for environmental assessment and management.	Effects of climate change /management decisions on the future dynamics of the coast.	• Storm surge flooding. • Coastal erosion.	• Emission scenarios. • Sea-level rise scenarios.
CVAT	• Coastal zones.	National legislation for environmental assessment and management.	To assess hazards, vulnerability and risks related to climate change and support hazard mitigation options.	• Storm surge flooding. • Coastal erosion. • Cyclone. • Typhoon. • Extreme events	• Past observations
DESYCO	• Coastal zones. • Coastal Lagoons	ICZM for environmental assessment and management.	To assess risks and impacts related to climate change and support the definition of adaptation measures.	• Sea-level rise. • Relative sea-level rise • Storm surge flooding. • Coastal erosion. • Water quality	• Emission scenarios. • Sea level rise scenarios.
DITTY	• Coastal Lagoons.	IWRM and WFD for environmental management.	To achieve sustainable and rational utilization of resources in the southern European lagoons by taking into account major anthropogenic impacts.	• ND	• ND
DIVA	• Coastal zones.	ICZM for environmental assessment and management.	To explore the effects of climate change impacts on coastal regions.	• Sea-level rise. • Coastal erosion. • Storm surge flooding.	• Emission scenarios. • Sea level rise scenarios.
ELBE	• River basin. • Catchment.	WFD for environmental management.	To improve the general status of the river basin usage and provide sustainable protection measure near the coast.	• Precipitation and temperature variation.	• Emission scenarios.

GVT	• Coastal zones.	National legislation for environmental assessment.	To describe the vulnerability of groundwater resources to pollution in a particular coastal region.	• Groundwater quality. • Saltwater intrusion.	• Sea level rise scenarios.
IWRM	• Coastal zones. • River basin	IWRM for environmental assessment and management.	To explore potential risks on coastal resources due to climate and water management policies.	• Sea-level rise. • Coastal erosion.	• Sea level rise scenarios. • Emission scenarios.
KRIM	• Coastal zones.	ICZM for environmental assessment.	To determine how coastal systems reacts to climate change in order to develop modern coastal management strategies.	• Sea-level rise. • Extreme events. • Coastal erosion.	• Sea level rise scenarios. • Extreme events scenarios.
MODSIM	• River basin.	IWRM for environmental management.	To improve coordination and management of water resources in a typical river basin.	• ND	• ND
RegIS	• Coastal zones.	SMP and Habitats regulation (UK) for environmental assessment and management.	To evaluate the impacts of climate change and adaptation options.	• Coastal and river flooding. • Sea level rise	• Emission scenarios • Socio-economic scenarios • Sea level rise scenarios
RAMCO	• River basin. • Coastal zones.	WFD and ICZM for environmental assessment and management.	For effective and sustainable management of coastal resources at the regional and local scales.	• ND	• ND
SimLUCIA	• Coastal zones.	National legislation for environmental assessment.	To assess the vulnerability of low-lying areas in the coastal zones and islands to sea level rise due to climate change.	• Sea-level rise. • Coastal erosion. • Storm surge flooding.	• Sea level rise scenarios.
SimCLIM	• Coastal zones.	ICZM for environmental assessment and management.	To explore present and potential risks related to climate change and natural hazards (e.g. erosion, floods).	• Sea-level rise. • Coastal flooding. • Coastal erosion.	• Sea level rise scenarios.
STREAM	• River basin. • Estuaries.	IWRM and WFD for environmental management.	To integrate the impacts of climate change and land-use on water resources management.	• Water quality variation. • Salt intrusion.	• Emission scenarios.
TaiWAP	• River basin.	IWRM for environmental assessment.	To assess vulnerability of water supply systems to impacts of climate change and water demand.	• Water quality variations.	• Emission scenarios.
WADBOS	• River basin. • Coastal zones.	WFD and ICZM for environmental assessment and management.	To support the design and analysis of policy measures in order to achieve an integrated and sustainable management.	• ND	• ND

Table 4. List of the examined DSSs according to the specific technical criteria

Name	Functionalities	Analytical methodologies	Structural elements
CLIME	• Identification of pressure generated by climatic variables. • Environmental status evaluation. • Water quality evaluation related to climate change. • Socio-economic evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Probabilistic Bayesian network. • Uncertainty analysis.	• Climatic, hydrological, chemical, geomorphological data. • Climate, ecological and hydrological models. • Web-based user interface
CORAL	• Evaluation of management strategies • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cost-effectiveness analysis. • Ecosystem-based.	• Environmental, socioeconomic, ecological, biological data. • Economic and ecological models. • Desktop user interface.
COSMO	• Problem characterization (e.g. water quality variation, coastal erosion etc.) • Impact evaluation of different development and protection plans. • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • MCDA. • Ecosystem-based	• Socio-economic, climatic, environmental, hydrological data. • Ecological, economic and hydrological models. • Desktop user-friendly interface.
Coastal Simulator	• Environmental status evaluation. • Management strategies identification and evaluation. • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Uncertainty analysis. • Risk analysis. • Ecosystem-based.	• Climatic, socio-economic, environmental, hydrological, geomorphological data. • Ecological, morphological climatic and hydrological models. • Desktop user interface.
CVAT	• Environmental status evaluation. • Hazard identification. • Indicators production. • Mitigation options identification and evaluation. • Spatial analysis (GIS).	• Hazard analysis. • Critical facilities analysis. • Society analysis. • Economic analysis. • Environmental analysis. • Mitigation options analysis.	• Environmental and socio-economic data. • Hydrological model. • Desktop user-friendly interface.

DESYCO	• Prioritization of impacts, targets and areas at risk from climate change. • Impacts, vulnerability and risks identification. • Indicators production. • Adaptation options definition • Spatial analysis (GIS).	• Regional Risk Assessment methodology. • Scenarios construction and analysis. • MCDA. • Risk analysis.	• Climatic, biophysical, socio-economic, geomorphological, hydrological data. • Desktop automated user interface.
DITTY	• Management options evaluation • Indicator production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Uncertainty analysis. • MCDA. • Social cost and benefits analysis. • DPSIR.	• Morphological, social, hydrological, ecological data. • Hydrodynamics, biogeochemical, socio-economic models. • Desktop user interface.
DIVA	• Scenarios generation and analysis. • Environmental status evaluation. • Indicators production. • Adaptation options evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cost-benefit analysis. • Ecosystem-based.	• Climatic, socio-economic, geography, morphological data. • Economic, ecological, geomorphological, climate models. • Desktop graphical user interface.
ELBE	• Environmental status evaluation. • Protection measures identification. • End-user involvement. • Spatial analysis (GIS).	• Scenarios construction and analysis.	• Hydrological, ecological, socio-economic, morphological data. • Economic, • Hydrological, models. • Desktop complex user interface.
GVT	• Environmental status evaluation. • Indicators production • Spatial analysis (GIS). • Impact and vulnerability evaluation	• Risk analysis. • Fuzzy logic. • MCDA.	• Data (environmental, climatic, hydrological, socioeconomic). Hydrological, socioeconomic and DEM models. • Desktop user interface.
IWRM	• Environmental status evaluation. • Indicators production. • Adaptation measures evaluation. • Information for non-technical users. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Risk analysis. • Cost-benefit analysis. • Socio-economic analysis.	• Climatic, environmental, socio-economic, geomorphological data. • Hydrodynamic, climate, economic models. • Desktop user interface.
KRIM	• Environmental status evaluation. • Adaptation measures evaluation. • Information for non-technical users. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact and risk analysis. • Ecosystem-based.	• Climatic, socio-economic, ecological, environmental, hydrological data. • Economic, ecological, hydrodynamic, geomorphological models. • Desktop user interface.
MODSIM	• Environmental status evaluation. • Management measures evaluation. • Spatial analysis (GIS).	• Statistical analysis. • Analysis of policies.	• Administrative, hydrological, socio-economic, environmental data. • Socio-economic, hydrological models. • Web-based user interface.

RegIS	• Indicators production • Management measures evaluation. • Information for non-technical users. • sectoral evaluation • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact analysis. • DPSIR. • Integrated assessment.	• Climatic, socio-economic, geomorphological, hydrological data. • Climate and flood metal-models. • Desktop user interface.
RAMCO	• Environmental status evaluation. • Indicators generation. • Management measures evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Cellular automata. • Ecosystem-based.	• Socio-economic, environmental, climatic data. • Biophysical, socio- economic and environmental models. • Web-based user interface.
SimLUCIA	• Indicators production. • Impact and vulnerability evaluation. • Management and land-use measures evaluation. • Spatial analysis (GIS).	• Cellular Automata. • Scenarios construction and analysis. • Socio-economic analysis. • Bayesian probabilistic networks. • Ecosystem-based.	• Climatic, environmental, socio-economic data. • Land use, social and economic, climate models. • Web-based user interface.
SimCLIM	• Environmental status evaluation. • Impact and vulnerability evaluation. • Adaptation strategies evaluation • Spatial analysis (GIS).	• Scenario construction and analysis. • Statistical analysis. • Risk analysis. • Cost/benefit analysis. • Ecosystem-based.	• Climatic, hydrological, socio-economic data. • Climate, hydrological, economic models. • Desktop user interface.
STREAM	• Environmental status evaluation. • Indicators production. • Management measures evaluation spatial analysis (GIS).	• Scenarios construction and analysis.	• Climatic, socio-economic, ecological, hydrological data. • Climate, hydrological models. • Web-based user interface.
TaiWAP	• Environmental status evaluation. • Indicators production. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Impact and vulnerability analysis.	• Climatic, socio-economic, hydrological data. • Climate, hydrological, water system dynamic models. • Desktop user interface.
WADBOS	• Management measures identification and evaluation. • Spatial analysis (GIS).	• Scenarios construction and analysis. • Sensitivity analysis. • MCDA.	• Socio-economic, hydrological, environmental, ecological data. • Socio-economic, ecological, landscape models. • Desktop user interface.

Table 5. List of the examined DSSs according to the applicability criteria (+++, highly flexible; ++, flexible; +: moderately to no flexible

Name	Scale and area of application	Flexibility	Status and availability Last updated version (year)
CLIME	• Supra National, National, Local. (Northern, western and central part of Europe).	+++ Flexible in structural modification and study area.	Available to the public. Demo. 2010.
CORAL	• Regional, Local. (Coastal areas of Curacao; Jamaica and Maldives).	+++ Flexible in study area.	Not available to the public. Prototype. 1995.
COSMO	• National, Local. (Coast of Netherland).	++ Flexible in study area.	Commercial application. 1998.
Coastal Simulator	• National, Regional, Local. (Coast of Norfolk in East Anglia, UK).	+	Available only to the Tyndall Research Centre. Prototype. 2009.
CVAT	• Regional, Local. (New Hanover County, North Carolina).	++ Flexible in study area.	Available to public. Prototype. 2002.
DESYCO	• Regional, Local. (North Adriatic Sea).	++ Flexible in study area.	Not available to the public. Prototype. 2010.
DITTY	• Supranational, National, Regional. (Ria Formosa-Portugal; Mar Menor-Spain; Etang de Thau-France; Sacca di Goro-Italy, Gera-Greece).	+++ Flexible in study area.	Not available to the public. 2006.
DIVA	• Global, National.	+++ Flexible in study area.	Available to the public. 2009.
ELBE	• Local. (Elbe river basin Germany).	+	Available to the public. 2003.
GVT	• Regional, Local. (Eastern Macedonia and Northern Greece).	+	Not available to the public. 2006.
IWRM	• Regional, Local. (Halti-Beel, Bangladesh)	++ Flexible in study area.	Not available to the public. Prototype. 2009.
KRIM	• Regional. (German North sea Coast, Jade-Weser area in Germany).	+	Not available to the public. Prototype. 2003.
MODSIM	• National, Regional. (San Diego Water County, Geum river basin- Korea).	++ Flexible in study area.	Available to the public online. 2006.
RegIS	• Regional, Local. (North-West, East Anglia).	++ Flexible in study area.	Available online to stakeholders. Prototype. 2008.
RAMCO	• Regional, Local. (Southwest Sulawesi coastal zone).	++ Flexible in the used dataset and concepts.	Not available to the public. Prototype. 1999.
SimLUCIA	• Local (St Lucia Island, West India)	+	Available online to the public. Demo. 1996.
SimCLIM	• National, Regional, Local. (Rarotonga Island, Southeast Queensland).	++ Flexible in structural modification and study area.	Available to the public. Demo. 2009.
STREAM	• Regional, Local. (Ganges/Brahmaputra river basin, Rhine river basin, Yangtze river basin and Amudarya river basin).	+++ Flexible in structural modification and study area.	Available online to the public. Demo. 1999.
TaiWAP	• Regional, Local. (Touchien river basin).	+	Available to National Taiwan University. Prototype. 2008.
WADBOS	• Regional, Local. (Dutch Wadden sea).	+	Available online to the public. Demo. 2002.

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CHAPTER 3

THE REFINEMENT AND ADAPTATION OF A REGIONAL RISK ASSESSMENT (RRA) APPROACH

3.1. INTRODUCTION

Climate change and its effects on water resources are increasingly becoming profound in human societies. In particular, changes in groundwater quantity and quality are now a huge challenge to human existence in the coastal communities where about 70% of the world population resides and in the arid and semi-arid areas where freshwater is already a crucial resource for survival (BGR, 2008; Voudouris et al., 2010 and Abd-Elhamid, 2010). The changes in groundwater conditions due to climate change and human activities (e.g., unsustainable extraction of groundwater, irrigation, waste and pollutants disposal, urbanization and land use changes) are critical sources of effects, which make groundwater unsuitable for domestic, industry, and irrigation purposes. Hence to understand the processes of these effects and to protect vital water resources, it is necessary to develop and apply appropriate methodologies and techniques.

In this thesis, a spatially resolved RRA methodology is proposed to enhance the understanding of a coastal groundwater aquifer and its dynamics, and how regional climate changes will alter the rate of this dynamics in the lower Esino River valley. In this context, the chapter presents the refinement and adaptation of a regional risk assessment (RRA) approach, which employs an integrated analysis of climate change impacts, vulnerability, and risks on the Esino coastal aquifer and dependent ecosystems according to the conceptual RRA framework, which complied with the Sources-Pathway-Receptor-Consequence (SPRC) framework (Ministry for the Environment of New Zealand, 2008). The SPRC framework was developed within the Euro-Mediterranean Centre for Climate Change (CMCC, www.cmcc.it) for the integrated assessment and management of climate change impacts on coastal systems and has been further revised and modified for specific coastal features like groundwater, to identify the key drivers of coastal groundwater hazards, possible targets and extent of potential risks, and thereby support the development of the spatially resolved regional risk assessment methodology.

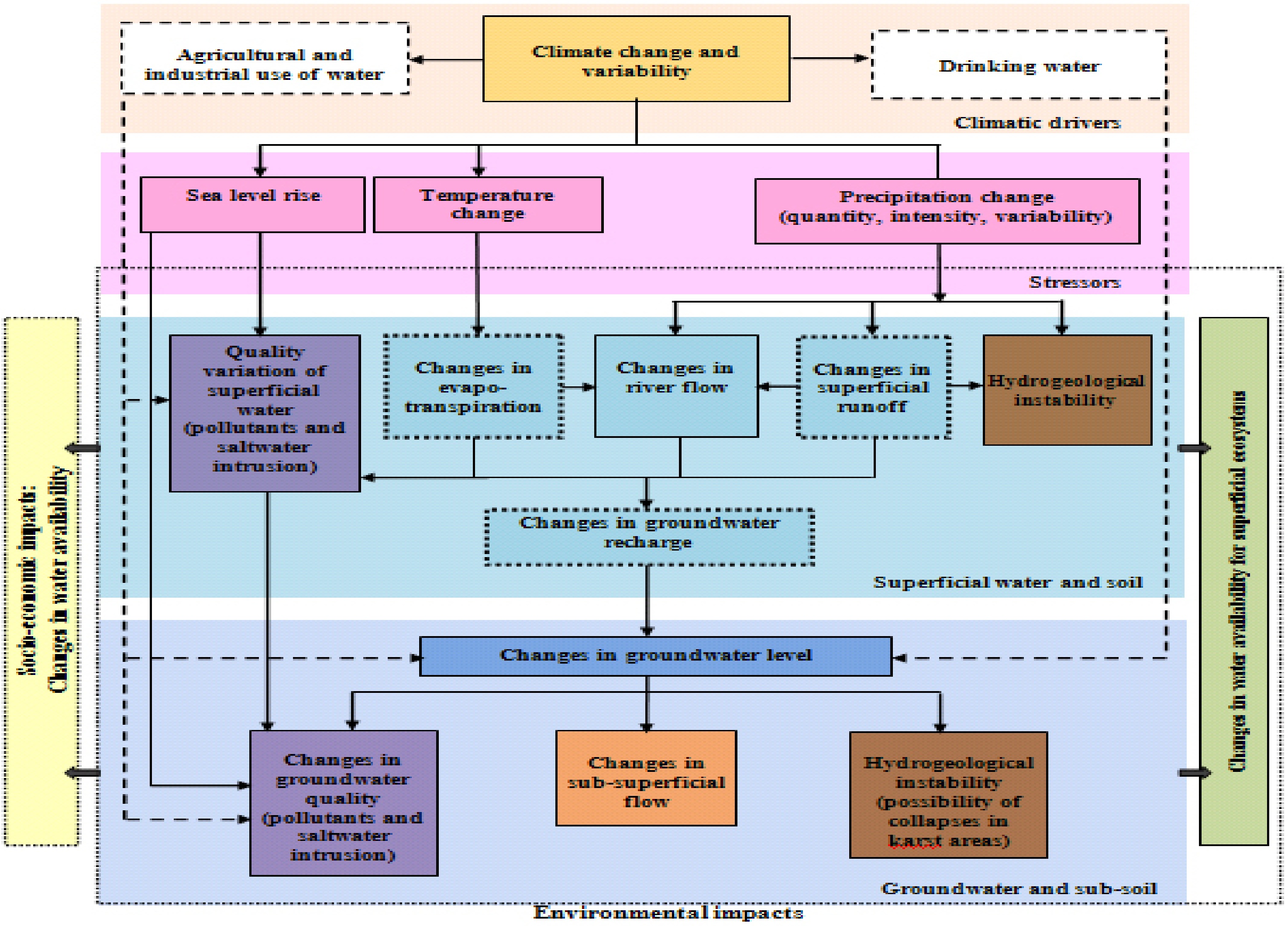
The spatially resolved RRA methodology considers relevant socio-economic and hydrogeological vulnerability, impacts and risks indicators with the aim to estimate effectively impacts on coastal systems. It could provide valid support for different stakeholders involved in the implementation of Integrated Coastal Zone Management (ICZM) and an important aid for national and regional water authorities in examining the possible consequences associated with environmental issues and adaptation measures. Traditionally, RRA 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 thesis, the RRA is defined specifically as a 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). This methodology 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 methodology considers the preliminary definition of frameworks 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 frameworks represent the main relationships between natural and anthropogenic forcing, generated stressors and consequent environmental and socio-economic impacts. They are 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.

3.2 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 3.2) represents main relationships between the primary drivers (climatic) of the natural and anthropogenic stressors, and the environmental and socioeconomic impacts generated.

Figure 3.2 Proposed framework describing cause and effect relationships among forcing, stressors, and socioeconomic and environmental impacts of climate change on groundwater and related ecosystems


Agricultural and industrial use of water
Climate change and variability
Drinking water
Climatic drivers
Sea level rise
Temperature change
Precipitation change (quantity, intensity, variability)
Stressors
Quality variation of superficial water (pollutants and saltwater intrusion)
Changes in evapo-transpiration
Changes in river flow
Changes in superficial runoff
Hydrogeological instability
Changes in groundwater recharge
Superficial water and soil
Changes in groundwater level
Changes in groundwater quality (pollutants and saltwater intrusion)
Changes in sub-superficial flow
Hydrogeological instability (possibility of collapses in karst areas)
Groundwater and sub-soil
Environmental impacts
Socio-economic impacts: Changes in water availability
Changes in water availability for superficial ecosystems

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.

3.3 THE RRA CONCEPTUAL FRAMEWORK

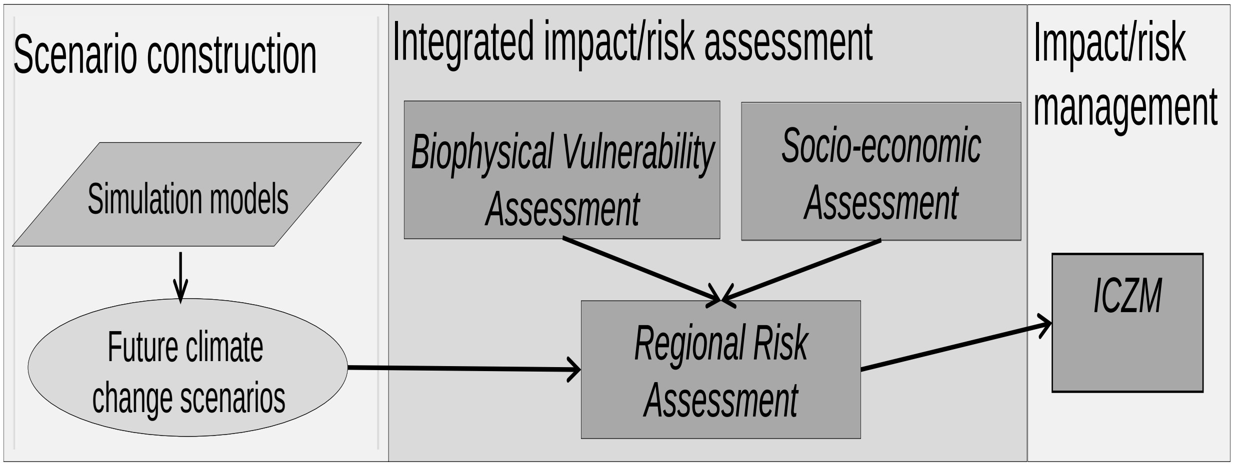
The spatially resolved RRA methodology also considers the conceptual RRA framework shown in Figure 3.3. This framework complies with the Source-Pathway-Receptor-Consequence (SPRC) approach, which allows to evaluate multiple sources of hazards (i.e. climate change and anthropic stressors) that may affect 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 methodology, 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* $(\boldsymbol{S_f})$, *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 methodology, 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 3.3 The RRA conceptual frameworks for the analysis of climate change impacts on coastal zone at the regional scale.



3.4 STEPS FOR THE SPATIALLY RESOLVED RRA METHODOLOGY

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

3.4.1 Regional risk matrixes (vulnerability and hazard)

The preliminary step to implement the spatially resolved methodology 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 is reported in Tables 3.4.1A. This matrix 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.

Table 3.4.1A. Vulnerability matrix for climate related impact (and respective legend)

RECEPTORS IMPACTS	RECEPTOR	RECEPTOR	RECEPTOR	RECEPTOR
CLIMATE CHANGE RELATED IMPACT	Pathway Factors	Pathway Factors	Pathway Factors	Pathway Factors
	Susceptibility Factors	Susceptibility Factors	Value Factors	Value Factors
	Susceptibility Factors	Value Factors		
	Susceptibility Factors			
	Value Factors			

Legend:	Pathway Factors	**Susceptibility Factors**	Value Factors

3.4.2 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.

3.4.3 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 (Preston et al., 2008). 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.

3.4.4 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.

3.4.5 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.

3.4.6 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.

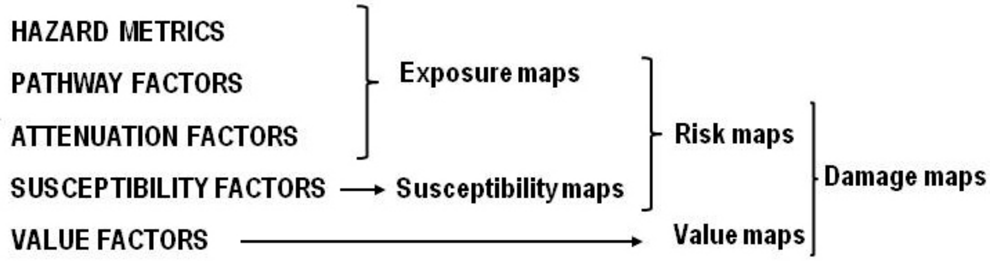
The Damage scores vary from 0 to 1. It assumes the higher score when risks are higher (i.e.1) and the value score is high, and assumes the minimum value (i.e. 0) when risks and/or the value are low (i.e. 0). In the other cases, the damage score assumes values in the range 0-1, and allows to identifying 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.

3.5 POTENTIAL OUTPUTS OF THE SPATIALLY RESOLVED RRA METHODOLOGY

The main outputs of the spatially resolved methodology 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 3.5, 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 3.5. Output maps scheme for spatially resolved methodology



3.6 CONCLUSIONS

Climate change and its present and potential consequences on water resources are increasingly becoming a huge challenge to mankind. The understanding that 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. In view of this, several studies have been focused on climate change impacts related to water resources, with much attention given to surface water than groundwater, despite the significant of the latter to human livelihood. Moreover, it has been established by most studies that climate change has already and will increasingly impact water resources especially groundwater (in terms of quantity and quality). This calls for the development and application of interdisciplinary methodologies and relevant tools useful to study the dynamics of groundwater systems due to climate change and anthropogenic pressures, to provide adequate information for groundwater resources planning and sustainable management mostly at the regional scale.

Accordingly, several methods and tools have been developed and applied with relevant indicators and indices to the study of groundwater problems due to climate change, ranging from investigation and control methodologies. In this context, the present thesis proposed a spatially resolved RRA methodology to further support the integrated management of climate change impacts on coastal groundwater resources and provide indications for the protection of groundwater-dependent ecosystems at the regional scale. The methodology offers a wide range of functionalities that can support the assessment of problems that affect coastal 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 coastal region. The methodology 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 methodology with the GIS-based DESYCO 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 coastal 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 within the region.

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CHAPTER 4

Regional risk assessment for climate change impacts on a coastal aquifer

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ABSTRACT

Climate change coupled with intense socio-economic activities in coastal regions will affect the state and characteristics of coastal systems. This calls for extensive analysis of future climate change scenarios and their effects on coastal water resources and related ecosystems.

This paper proposes a regional risk assessment approach to evaluate potential climate change-related threats on coastal aquifers and dependent ecosystems, and to prioritize targets and areas potentially at risk. The paper attempts to contribute to previous methodologies that have been devoted to coastal ecosystems issues related to climate changes, as well as to respond to the urgent need for vital coastal ecosystems' protection and management.

Relevant impacts, such as Groundwater Level Variations and Saltwater Intrusion were systematically and quantitatively analysed through the spatial characterization of hazard scenarios and the assessment of exposure, susceptibility, risk and damage. The approach employed future climate change scenarios with reference to four different seasons (winter, spring, summer and autumn), which were constructed using the results of a chain of climate, hydrology, hydraulic and groundwater systems models within 2070-2100 timeframe and according to the IPCC SRES A1B emission scenario. In order to provide potential relative risks indications responding to water managers' needs for the implementation of the key principles of the Water framework Directive and Groundwater Directive.

The results indicate that in the future scenarios and seasons, climate change will exert slight disparity in impacts on the lower Esino River valley. Groundwater level variation impact in the summer season will have limited effects, i.e. only on specific agricultural areas and forests and semi-natural systems located along the coastline and surface water bodies. Saltwater intrusion impact in the future seasons will be restricted to a narrow region close to the coastline, and thus it is expected to have limited effects on the Esino coastal aquifer and fewer consequences on dependent ecosystems.

***Keywords**:* Climate change, Esino coastal aquifer, groundwater dependent ecosystems, RRA

1 INTRODUCTION

Coastal groundwater resources connect the world's oceanic and hydrologic ecosystems (Moore, 1996; Ferguson and Gleeson, 2012) and play vital roles in the socio-economic and ecological functions of coastal systems worldwide (IPCC, 2007b). However, current research indicates that climate variability and climate change will constraint the usefulness of coastal groundwater through changes in climate variables (e.g. temperature, precipitation and evapotranspiration) and concomitant changes in sea level (Sherif and Singh, 1999; Ranjan et al. 2006; Jyrkama and Sykes, 2007; Herrera-Pantoja and Hiscock, 2008; Ferguson and Gleeson, 2012; Bates et al., 2008). Thus, coastal groundwater-dependent ecosystems (e.g. agricultural areas, natural systems, surface water bodies, etc.), will be prone to impacts related to changes in groundwater quantity and quality (Bates et al., 2008; Dragoni and Sukhija, 2008; Essink, et al., 2010; Abd-Elhamid, 2010; Abd-Elhamid and Javadi, 2011). Moreover, according to several studies (e.g., Bates et al., 2008; Dragoni and Sukhija, 2008; Abd-Elhamid, 2010; Franssen, 2009; Baba et al., 2011; Praveena and Aris, 2010), climate change would bring impact on coastal groundwater directly, through the interaction with surface water bodies, and indirectly, through the aquifers' recharge processes. But the extent to which these resources will be affected depends largely on the region's hydrogeological features and soil properties, and also on unsustainable human exploitation of aquifers and excessive use of soil (Herrera-Pantoja and Hiscock, 2008; Werner et al., 2012).

A number of persuasive studies of coastal groundwater resources' interactions with climate change and anthropogenic pressures developed by Ferguson and Gleeson (2012), Franssen (2009), Clarke et al. (2010), Re and Zuppi (2011) revealed that these interactions would affect global coastal aquifers differently, mostly in the coastal arid and semi-arid regions, where groundwater shortage is already aggravated by recurrent droughts and by its excessive use for socio-economic activities (mainly in coastal communities, where half of the world's population lives and 8 of the 10 largest cities in the world are currently located) (Post, 2005; Carneiro et al. 2010).

However, in general, climate change interactions with global water resources, and particularly with coastal groundwater aquifers, are well established, even though potential climate change effects at the regional scale are still uncertain. This is mainly due to the uncertainty related both to projections of climate variables (Baruffi et al., 2012) and the simulation of coastal aquifers' small-scale processes, such as spatial heterogeneities, geo-chemical reactions and hydrogeological changes that often demand detailed information about subsurface areas (Werner, 2009; Scibek and Allen, 2006). On numerous occasions this has resulted in poor research and understanding of the links between climate change and coastal groundwater resources, and its dependent ecosystems.

As a result of these uncertainties, coastal groundwater resources' monitoring and investigation has been much discussed in recent studies both at the global scale (e.g. IPCC, 2007a; Barron et al., 2010; Werner, 2010) and at the regional scale (e.g. Bear et al., 1999; Holman, 2006; Herrera-Pantoja and Hiscock, 2008; Post and Abarca, 2010; Clarke et al., 2010; Essink, et al., 2010; Gemitzi and Stefanopoulos, 2011; Barron et al., 2012; Dams, J., et al., 2012), focusing on the assessment of climate change interactions with coastal groundwater resources through recharge and contamination processes. But none of these systematically considers the potential risk, on coastal aquifer and on a variety of dependent ecosystems. A few studies (e.g., Barron et al., 2012; Klove et al., 2011) considered the effects of potential climate change on surface and groundwater dependent vegetation and also highlighted the need to evaluate hydro-ecological status and trends of groundwater-dependent ecosystems, but they did not actually assess and prioritize potential climate change risks for several dependent ecosystems.

In view of this research gap, the present paper offers a comprehensive regional risk assessment approach based on an ecosystem perspective (UNEP, 2009; http://www.cbd.int/ecosystem/) to adequately account for the complexity of coastal systems and their mutual interrelated impacts and to establish a causal link between identified stressors and possible receptors and areas (via ecological pathways). Accordingly, the paper proposes a spatially resolved Regional Risk Assessment (RRA) methodology 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 methodology was based on the RRA conceptual framework (Figure 2) applied within the European Life+ SALT (Sustainable mAnagement of the Esino river basin to prevent saline intrusion in the coastaL aquifer in consideration of climaTe change, www.lifesalt.it) project, to analyse potential climate change impacts and risks on regional coastal groundwater resources in the Esino river basin (Italy). SALT was a pilot project intended to create a model for the implementation of two EU policy instruments, the Water Framework Directive (WFD, 2000/60/EC) and the Groundwater Directive, (2006/118/EC), in the lower Esino river valley of the Marche region (Italy). For this purpose, the spatially resolved RRA methodology developed within the Euro-Mediterranean Centre for Climate Change (CMCC, www.cmcc.it), was applied to evaluate potential groundwater quantity and quality related impacts on the Esino coastal aquifer and associated ecosystems through the characterization of climate change hazard scenarios and the assessment of exposure, susceptibility, risks, and damages.

In the following sections, the case study area is introduced and the methodology is discussed through the application to the Esino river basin. Moreover, significant results related to exposure, susceptibility and risk maps produced for the defined climate change scenarios are analysed in order to highlight areas and receptors at risk to climate-related impacts.

2. THE CASE STUDY AREA

The case study area is represented by the lower Esino river valley (Figure 1), which is situated in the Marche region in central Italy. The Esino river basin is an area of about 1,203 square kilometres and the river length is about 86 km, from the Cafaggio Mountain in the province of Macerata, to the municipality of Falconara Marittima, where it flows into the Adriatic Sea. The region's topography reveals two Apennines ridges, the Umbria-Marche ridge and the Marche ridge surround the Esino River valley). Moreover, the valley is generally steep-sided, narrow and deep with alluvial flood plains that extend wider eastward up to more than 10 km close to the Adriatic coast (Calderoni et al., 2007). Clays and marls define the region's geomorphology with millimetric silty-sandy layers from silicilastic turbiditic synorogenic deposit (Alberti et al., 2009), often covered by alluvial deposits (from the Quaternary) to form the unconfined aquifer system. The region's alluvial deposits increase in thickness from the inland towards the coastline, due to previous Esino erosion action, and mainly comprise gravel, gravelly-sandy, and gravelly-clay with intercalated lenses of sand, clay and sandy silty clay (Coltori 1999; Nanni, 1985; Alberti et al. 2009).

The climate varies from sub-continental along the coast in the north to temperate in the inland areas toward the south (with the seasonal variations in temperature). However, meteorological variables studied in the region of Jesi revealed that the average annual temperature is 14.4°C and the cumulated precipitation is 826.9 mm/year (Bordi et al. 2001). This often resulted in torrential floods in the catchment during autumn and winter, characterized by the continuous buoyancy of the Esino River bed during the full fall-winter and decreased flow during late spring and summer, with consequent strong influence on the environmental conditions.

The lower Esino river valley's location on the side of Adriatic coast makes it more vulnerable to potential impacts from natural and anthropogenic origin. In particular, the rapid growth in human population and urbanization within the Adriatic coastal area and the presence of hazardous plants and industrial infrastructures further accelerate this vulnerability. Moreover, the area is home to traditional agriculture for more than 100 square kilometres (about 90% of the total surface) and few natural or semi-natural zones (7 square kilometres, about 5% of the total surface), mainly located along the Esino Riverbed. The high demand for freshwater by the population, the unsustainable management of urban wastewater and the increased use of fertilizers in agriculture not only increases pressures on the region's confined and unconfined shallow aquifers but also impact groundwater quality and quantity (www.lifesalt.it/en/idea.html). Thus, the Esino wells and surface water supply network are affected by uncontrolled pollution loads untreated discharge and combined sewer overflows (Biondi & Baldoni, 1993; Biondi et al. 2003). Climate changes will exacerbate these phenomena through changes in natural recharge processes of the unconfined and confined aquifers and rising Esino River levels due to variations in seasonal temperature, precipitation and evapotranspiration over the period of 2070-2100 (Bucchignani and Gualdi, 2011).

3. MATERIALS AND METHOD

The following paragraphs present the integrated modelling approach, and the spatially resolved regional risk assessment methodology employed to analyse potential effects of climate change on the Esino coastal aquifer and dependent ecosystems.

3.1 Model chain applied to the lower Esino River valley.

To simulate relevant climate, circulation, hydrological and hydrogeological processes that may influence climate change impacts on groundwater resources at different spatial scales, the model chain shown in (Figure 3 appendix A) was applied to bridge the gap between large scale climate scenarios, often defined by global circulation models (GCM), and the fine scale scenarios where local impacts happen as a result of changed climate conditions. Accordingly, the proposed model chain includes climate, hydrological, hydraulic and groundwater models.

The Global Ocean and Mediterranean Sea model (CMCC-MED) used to perform the case study area's present and future climate projections includes the coupled Atmosphere-Ocean Global Circulation Model (AOGCM) linked with a high resolution Mediterranean Sea model (OPA/ORCA2 and NEMO/MFS). The AOGCM consists of a global atmosphere model (ECHAM5.4; Roeckner et al., 2003), implemented with 31 vertical levels and a horizontal resolution of about 80 km, and a global ocean model (OPA 8.2; Madec et al., 1998) with a horizontal resolution of about 2° and 31 vertical levels, which includes the dynamic model of the sea ice LIM (Fichefet and Maqueda, 1999). The Mediterranean Sea model is an interactive model implemented with a horizontal resolution of 1/16° and 72 non-uniform vertical levels. Output from these global models are used to implement a limited area (regional) climate model (COSMO-CLM; Rockel et al., 2008) in order to increase the spatial resolution of the climate change projections and their suitability for climate change studies in the Esino River basin. Moreover, the high horizontal resolution of COSMO-CLM allows a better description of orography, and thus, an improved representation of small-scale physical processes related to terrain height and land-sea contrast. The model has been implemented on the domain 2-20°E, 40-52°N, with a horizontal resolution of about 8 Km and 40 vertical levels. Climatic variables (i.e.

temperature, precipitation and evapotranspiration) projections by these climate models were used to perform river basin catchments hydrological simulations for precipitation and runoff processes using the hydrological model HEC-HMS and the hydraulics model HEC-RAS.

The Hydrological Modelling System (HEC-HMS) is public domain software developed by the United States Army Corp of Engineers to simulate the precipitation-runoff processes of dendritic watershed system. It is applied for problem solving in the field of large river basin water supply and flood hydrology and small urban or natural watershed runoff. In the SALT project, the HEC-HMS model was linked with the ArcView GIS software using the Geo-HMS extension in order to provide tools for pre-processing of the terrain, perform spatial analysis, delineate sub-basins and streams and construct inputs to the HEC-HMS hydrological models. Thus, using Geo-HMS, the river catchment was modelled, calculating the main physical parameters (i.e. length and slope of the river course, and drainage path length of the sub-basins) over the entire Esino watercourse. The results of the Esino watershed basin modelling with Geo-HMS reflect the basin's continuous hydrological flow: an input to the hydraulic model (HEC-RAS) for estimation of surface water level.

The River Analysis Systems (HEC-RAS) used to perform the basin river analysis is public domain software developed by the United States Army Corp of Engineers to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The HEC-RAS system contains four one-dimensional river analysis components for: 1) steady flow water surface profile computations; 2) unsteady flow simulation; 3) movable boundary sediment transport computation; 4) water quality analysis, including detailed temperature analysis and transport of a limited number of water quality constituents (i.e., algae, dissolved oxygen, dissolved ammonium nitrate, dissolved nitrite nitrogen, carbonaceous biological oxygen demand). A key element is that all four components use a common geometric and hydraulic computation routine. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed in order to clearly identify dynamic water surface levels from HEC-RAS simulation, which are allocated to correspondent elements in the groundwater model (FEFLOW) to simulate transmission between the river and aquifer.

Finally, the FEFLOW software is a 3D finite element subsurface model for flows and transport simulation, which is particularly suitable for salt intrusion analysis, being able to simulate density dependent flows. The FEFLOW provides best-in-class capabilities for porous-media simulations on scales ranging from millimetres to hundreds of kilometres, from milliseconds to thousands of years. The supported processes are: fluid flow, density dependent flow, reactive solute transport, heat transport, saturated and variably saturated and unsaturated conditions, and fracture flow. Thus, FEFLOW outstanding range of applications includes: regional groundwater management, groundwater management in construction and tunnelling, mine water management, saltwater intrusion, seepage through dams, open-loop and closed-loop geothermal systems, deep geothermal installations, industrial porous media. Within the SALT project, a digital terrain model (DTM) of the Esino coastal aquifer was constructed using stratigraphy data from regional wells, in order to reflect the study area topography and identify and report its four geological units (i.e. gravel-clay, clay-sand, gravel-sand and the impermeable aquiclude) in the FEFLOW 3D model. Saltwater intrusion into the aquifer was simulated after proper calibration, using data from existing literature regarding recharge processes and Esino river-aquifer exchange.

3.2 Spatially resolved Regional Risk assessment Methodology.

The spatially resolved Regional Risk Assessment (RRA) methodology is developed to evaluate potential climate change impacts and risks on the Esino coastal aquifer. It considers multiple sources of hazards related to changes in the precipitation regime, river flow discharge, and groundwater depth and quality. These may affect the status and conditions of coastal groundwater-dependent ecosystems (e.g. wells, river, agricultural areas, lakes, and forests and semi-natural environments), selected as targets/receptors in the case study area application. Relevant climate variables were considered to construct potential climate change hazard scenarios, in order to effectively quantify regional coastal groundwater impacts from climate change. In particular, relevant impacts considered by the methodology are: 1) Groundwater Level Variation (GLV), which signify the potential changes in the water table due to the alteration of recharge processes from climate change and excessive pumping of groundwater; 2) Saltwater Intrusion (SI), which refers to the subsurface movement of seawater into coastal aquifer, either from climate variations and consequent fluctuating sea levels or lowering of local wells potentiometric surface, and its resultant up-coning of saline water into the freshwater zone, due to excessive pumping of groundwater. Together, they affect the quantity and quality of coastal groundwater and the ecological status of dependent ecosystems.

In order to identify key areas and targets/receptors at risk from climate change impacts on the coastal aquifer and dependent ecosystems the proposed spatially resolved RRA includes six major steps:

1. Definition of the regional risk matrix
2. Hazard assessment
3. Exposure assessment

4. Susceptibility assessment
5. Risk assessment
6. Damage assessment

Accordingly, the following paragraphs describe and discuss these steps and illustrate the results of their application to the lower Esino river valley case study area, including exposure, susceptibility, risk and damage maps.

3.2.1 Regional risk matrix: vulnerability and hazard data input

The first step of the spatially resolved RRA methodology concerns the definition of a regional risk matrix, which identifies all the components contributing to the computation of risk in the case study area (i.e. stressors, receptors and impacts) and their relationships (Torresan, 2012; Torresan et al., 2012). The regional risk matrix is composed of two distinct sub-matrixes: the vulnerability matrix, which supports the assessment of the case study area's vulnerability to climate change at the regional scale. The second is the hazard matrix that guides the identification of climate change hazard metrics/parameters and thus the construction of hazard scenarios.

Accordingly, in this application, the hazard matrix (Table 2 appendix A) concerns the identification of relevant stressors with reference to GLV and SI impacts and their related hazard metrics. These metrics were derived from relevant outputs of the model chain described in section 3.1, as statistics for the characterization of climate change hazard.

The vulnerability matrix (Table 1 appendix A) highlights the receptors/targets identified in the case study area (Table 3 appendix A) to describe the environmental components that could be affected by multi-interrelated climate change impacts, such as GLV and SI. The matrix also includes sub-cells of vulnerability factors, categorised into susceptibility, value and pathway factors, which are clearly defined in (Table 4 appendix A). According to Torresan (2012), susceptibility factors depict the degree to which targets/receptors could be affected either adversely or beneficially by climate-related hazards and are represented by the ecological and hydrogeological features of the considered region. Value factors represent relevant environmental and socio-economic properties or features of the examined targets or receptors that need to be preserved. Finally, pathway factors denote the physical characteristics of targets/receptors that can influence their possible contact with climate change hazards and thus support the identification of potentially exposed areas.

For the purpose of this application, these factors were defined using data extracted from several sources, including the European Corine Land Cover 2006 (www.eea.europa.eu/publications/CORO-landcover), data from Esino river hydrological modelling and monitoring experiences at regional and local scale, wells information and location data within the area, and socio-economic datasets of agricultural products, as reported in (Table 5 appendix A). According to the available datasets, a specific grid cell of 25m was considered for the analysis of each spatial unit of the defined areas and receptors.

3.2.2 Hazard assessment

The hazard assessment aimed at the spatial characterization of climate change hazard scenarios, which describes potential climatic hazard conditions against which a system/region needs to adapt in order to maintain its ecological and socio-economical functions. Within the spatially resolved RRA methodology, hazard characterization is based on the aggregation of multiple hazard metrics/variables defined within the hazard matrix (Table 2 appendix A). For each one of the investigated impacts, these metrics/variables were selected as relevant statistics and were derived from the applied model chain (section 3.1).

These projections were focused on seasonal scales (i.e. winter, spring, autumn and summer), in order to evaluate possible seasonal changes in climatic trends within the Esino River basin, and particularly to determine how potential changes in the precipitation regime of the present timeframe (2000-2008) could be influenced by projected climatic trends for the future timeframe (2070-2100) at seasonal level. Moreover, such analysis was performed considering seasonal precipitation patterns referred to three different representative years in the present timeframe (i.e., the driest, the average and the wettest years), in order to provide a complete description of the investigated effects. Thus, in this application, different precipitation scenarios (s) were defined to represent the future seasonal average of the precipitation regime with reference to the four different seasons and the three representative years, and they were considered as the future climate change scenarios useful to assess climate-related hazards for each examined impact (k).

For the GLV impact, the hazard is represented by the reduction of future water table depth, as a result of climate changes and anthropogenic activities. This is specifically identified by the difference between the future timeframe groundwater depth and the present timeframe groundwater depth, where a reduction in water table is expected.

The GLV related hazard refers to seasonal changes in the average groundwater depth, which were derived from the ensemble modelling applied to different precipitation scenarios. Thus, the GLV hazard related statistics consider the seasonal average groundwater depth that was based on daily mean groundwater depths for the case study area. Daily mean groundwater depths were averaged to estimate the seasonal mean groundwater depth that was considered as key hazard metric for the

GLV hazard, because the minimum depletion of groundwater depth in a shorter time frame do not reflect actual effects on dependent ecosystems due to soil water retention capacity.

For SI impact, the hazard is related to the potential increase of the saline wedge level within the aquifer due to the reduction in the water table which is consequent to significant pressures from human activities, climate changes and concomitant sea level rise. The hazard is thus identified by changes in the saline interface depth (saline wedge) between freshwater in the coastal aquifer and seawater. Such changes were derived considering the difference between saline wedge depth values in the present timeframe (2000-2008) and in the future timeframe (2070-2100). The saline interface was identified according to the Italian standards for ground water quality (DPR 236/88, 1988), i.e. where the saline concentration is higher than the threshold of 1300 mg/l.

In more detail, potential changes in the saline interface depth were analysed with reference to each season, i.e. considering the seasonal average values of the saline interface depth in order to characterize potential SI hazard at seasonal scale.

3.2.3 Exposure Assessment

Exposure assessment is aimed at identifying and classifying possible impacted areas or valuable receptors in the lower Esino river valley. Thus, it aggregates the estimated hazard metrics ($h_{s,k}$) with the identified pathway factors (p), according to relevant exposure functions defined for each of the investigated climate change impacts.

Exposure analysis by Equations 1 and 2 (Table 7 appendix A) resulted in exposure scores in the range between a minimum value of 0 and a maximum value of 1. The minimum value refers to no exposure of the areas/receptors, while maximum value represents extreme exposure of areas/receptors compared with other receptors in the case study area. Accordingly, exposure scores do not allow to estimate climate change exposure in absolute terms, rather it provides relative evaluation of potential areas or receptors exposed to climate-related hazards.

In particular, Equation 1 was considered in the GLV impact's exposure analysis, while Equation 2 was considered for that of SI impact. Both these equations were based on the following specific assumptions: 1) the more variations in groundwater/saline interface depth, the more receptors lying on top are harmed; 2) the pathway through which groundwater/saltwater can reach receptors was defined as the groundwater/saline interface mean depth, which in practice represents the soil lying between the ground surface and water table/saline interface; 3) The increase/decrease of groundwater/saline interface depth is impacting only receptors lying at a distance equal or less than a predefined susceptibility threshold (s_1 or s_2). The values s_1 and s_2 depict changes in groundwater/saline interface depth that could impact specific receptors lying at a distance equal or less than a predefined value. They were selected based on available literature's data and on the judgements of different experts/researchers, and relevant stakeholders. Accordingly, the values of s_1 and s_2 were defined as 3m for all the receptors in the entire considered region, except in a buffer zone of 50m around the river mouth where was 2m. A different technical threshold (i.e. 10m) was also chosen for all the considered shallow wells, considering the localization of the well filters. These thresholds allow analysts to identify areas and receptors, which are connected to the shallow groundwater aquifer at present and to exclude areas not directly linked to such aquifers (or which are not directly linked to salt groundwater).

The exposure analysis for the GLV impact was focused on potentially exposed groundwater-dependent ecosystems (i.e. agricultural areas, river, lakes, forests and semi-natural environments). A higher increase in groundwater depth corresponds to an increase of the potential harm for the considered receptors.

As far as the SI impact is concerned, the exposure analysis was focused on the potential exposure of the same receptors to future changes in saline interface depth, due to the potential movement of saline wedge interface inland. A higher potential harm for the considered receptor is caused by a decrease of the saline interface depth.

3.2.4 Susceptibility Assessment

The susceptibility assessment for the GLV and SI impacts was carried out using the susceptibility factors identified in the vulnerability matrix (Table 1 appendix A). These factors have been classified assigning susceptibility scores according to data from existing literature and expert judgements. Thus, susceptibility classes were determined by thresholds that reflect variations in the degree to which the case study area may be affected by climate-related impacts. In accordance with specific features, for each factor a discrete set of classes and related scores were defined and evaluated, as reported in (Table 6 appendix A). The susceptibility scores represent the relative susceptibility value of each single class, ranging from 0 (i.e. no susceptibility) to 1 (i.e. maximum susceptibility). Susceptibility factors for the GLV impact involved qualitative classes defined for *vegetation cover typology* and *crop typology* factors, which were initially defined according to the Corine Land Cover 2006 map, and then aggregated according to crops typology with similar water needs. These classes were finally scored in the 0-1 ranges, assigning the highest score (i.e., 1) to the most water demanding crops, and intermediate and low scores (i.e., 0.7 and 0.3) to others. Quantitative classes were defined for *extension of forest; basin extension, river flow* and *average volume yearly extracted from wells* factors. For the *extension of forest* and *basin extension* factors, classes were defined by dividing factors' extension (sq.km) range in 5 and 2 classes respectively, according to the equal interval method (ESRI Inc., 1995), in order to normalize them in the range of 0-1. Thus, susceptibility scores were assigned considering that the smaller is the receptors' surface area, the higher their susceptibility to hazards related to groundwater depth decrease. In addition, for *River flow* and *Average volume yearly extracted from wells* factors, classes were defined using a similar approach, but considering relevant measured data provided by partners involved in the SALT project (Table 5 appendix A). For such factors, susceptibility scores were assigned in the range from 0.2 (i.e. lowest susceptibility) to 1 (i.e. highest susceptibility). This is because, for example, the more average volume of water yearly extracted from wells; the more these wells will be sensitive to GLV related hazard.

For SI impact, quantitative classes were defined for *water salinity, basin extension, riverbed slope* and *river flow*. For the *basin extension* factor, classes were defined in consideration of the two lakes' extension (sq.km), and scores were assigned according to the same procedures adopted for GLV impact and explained above. The *water salinity* factor, which is related to the Esino River aquifer subsurface flow modelling data obtained from four different gauge stations, five classes were defined using the equal interval method (ESRI Inc., 1995), and susceptibility scores assigned based on the following assumption: higher conductivity would result in higher susceptibility to saline contamination in unconfined coastal aquifer. In addition, classes related to *river flow* and *river bed slope* factors were defined using the aforementioned equal interval method, considering data related to the Esino River flow (m^3/s) and its hydro-morphology respectively. The related susceptibility scores were assigned according to the following assumption: higher river flows in terms of the average will lead to lower susceptibility of coastal aquifer freshwater to saline contamination, since higher river flows move more water toward the seabed and thus, increase the dilution of saltwater.

According to the vulnerability matrix in (Table 1 appendix A), susceptibility factors were not identified for wells and agricultural areas. However, a maximum susceptibility score (i.e. 1) was assigned to wells with reference to SI impact because it was assumed that salt water could compromise their use. Agricultural areas were also assigned a susceptibility score (i.e. 1) considering the precautionary approach, because the available data did not provide detailed information to identify areas that are not affected in the same way by salt water and to distinguish between areas, including halophytes and glycophytes.

Finally, susceptibility factors were further analysed by assigning equal weight (i.e. 1) to all the considered factors in order to give the same importance to all susceptibility parameters in the final computation of susceptibility. Moreover, susceptibility scores were aggregated using the

MCDA function Probabilistic-or, as shown in Equation 3, to provide the relative rank of areas and receptors more sensitive to GLV and SI impacts.

$$\overline{S_k = \otimes_i^n \left[sf'_{i,k}\right]}$$ **Equation 3**

Where:

S_k = Susceptibility score of the cell to the impact ***k***;

$\otimes$ = “Probabilistic or” function;

$sf'_{i,k}$ = Normalized i^{th} susceptibility factors related to the impact k;

3.2.5 Risk Assessment

The risk assessment aimed at identifying and ranking areas and receptors at risk to GLV and SI impacts in the lower Esino river valley. It concerns the integration of information related to exposure and susceptibility produced in the exposure assessment (section 3.2.3) and susceptibility assessment (section 3.2.4) phases respectively. However, within the RRA methodology, regional risks estimations are not absolute predictions of 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. In this context, risk assessment is based on relative risk scores ($R_{k,s,i}$) obtained for the investigated impacts as the product of exposure scores $E_{k,s}$ (section 3.2.3) and the susceptibility scores $S_{k,i}$ (section 3.2.4) according to the risk function expressed by Equation 4.

$$\boldsymbol{R_{k,s,i} = E_{k,s} \cdot S_{k,i}}.$$ **Equation 4**

Where:

$R_{k,s,i}$= Relative risk related to hazard k, scenario s and receptor i

$E_{k,s}$= Exposure related to hazard k, in the scenario s

$S_{k,i}$ = Susceptibility related to hazard k, and receptor i

Accordingly, the estimated risk scores vary 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 to the considered impacts) and 1 means higher risk for considered receptors/areas in the region.

3.2.6 Damage Assessment

This provides the relative estimation of potential social, economic and environmental losses of receptors and areas at risk in the considered region. The damage assessment considers the integration of risk scores (section 3.2.5) with value scores, the latter is obtained from the estimation of environmental and socio-economic features of receptors and aggregated using a specific value function (i.e. additive procedure). The estimation of receptors' value scores requires the definition of classes and associated scores for the selected value factors. Accordingly, value factors defined in the damage assessment of GLV and SI impacts (Table 6 appendix A) include *protection level, crop economic value, and extension of forest, vegetation covers typology* and *well uses typology*. These factors were selected considering data from existing literature related to the case study area and opinions from relevant stakeholders. Further useful insights are taken from the Corine Land Cover 2006 maps in order to support the definition of classes and associated scores for selected factors.

The value factors classification followed the same procedure of the one proposed in section 3.2.4 for susceptibility factors. Qualitative value factors are represented by *protection level*, *vegetation cover typology* and *well use typology*. The classification of the *protection level* factor was based on the level of importance of the regulation which defined each protected area: areas protected at the European level (i.e. SPAs and SACs sites of Natura 2000 network) had the highest value score (i.e. 1), Parks and Reservoirs had an intermediate score 0.6, while unidentified areas were classified with the lowest score (i.e. 0.2). As far as *vegetation cover typology* is concerned, the value score was assigned based on the economic and naturalistic value of the vegetation cover; accordingly forests had the highest score while scrub/herbaceous vegetation and sparse vegetation had an intermediate (i.e. 0.7) and the lowest (i.e. 0.3) value scores respectively. Finally, for *well use typology* scores were defined based on the different categories of wells usage (e.g. domestic, industrial, agriculture, irrigation, drinking and other purposes). The most important uses, i.e. domestic/drinking, were assigned 1, while less important uses, i.e. industries supply, were assigned 0.7 and least important use, i.e. agriculture/irrigation, were assigned 0.5.

The classification of the two quantitative factors, i.e. *crop economic value* and *extension of forest,* was made dividing the range of values of each factor into five equal intervals.

Thus, the spatially resolved methodology employs the value function (V_i) expressed by equation 5 to aggregate value factors' scores, and thus estimate relevant environmental and socio-economic values of the considered areas and receptors.

$$V_i = \frac{\overline{\sum_{i=1}^{n}[vf'_{i,i}]}}{n}$$

Where:

vf_{1_n} = Factors related to value

n = Number of value factors

Finally, the damage function expressed by Equation 6 is applied to integrate the calculated risk scores (section 3.2.5) with the aggregated value scores, to determine possible damages for areas/receptors with respect to GLV and SI impacts in the future scenarios.

$$\boldsymbol{D_{k,s,i} = R_{k,s,i} \cdot V_i} \quad \textbf{Equation 6}$$

Where:

$D_{k,s,i}$ = Damage scores related to hazard k, and a receptor i in scenario s,

$R_{k,s,i}$ = Risk scores related to hazard k and receptor i in scenario s,

V_i. = Value scores of receptor i

In this way, damage scores were calculated for all the examined receptors in the case study area, including relevant statistics (e.g. percentage of the total surface area of each receptor associated to each damage class and territorial surface of each receptor with higher damage scores for each administrative unit, etc.)

4 RESULTS AND DISCUSSION

The main results of the performed RRA include GIS-based maps describing spatial changes in exposure, susceptibility, risk and damage to GLV and SI impacts. In addition, relevant statistics were calculated to further analyse these maps, in order to systematically and quantitatively characterize future climate change trends, which could affect areas and receptors in the lower Esino River valley.

The relevant GIS maps and their related statistics from the case study area application are thus presented and discussed below.

4.1 Exposure maps

Exposure maps for GLV impact revealed slight differences among different seasons, within the same analysed scenario (section 3.2.2), and negligible difference comparing different scenarios. Thus, the current analysis was focused on the summer season of an average year, to possibly emphasize extreme effects of future drought periods due to climate changes, providing relevant indicators to prioritize and strengthen current strategies for regional water resources planning and management.

The exposure map (Figure 4 appendix A) shows that potentially exposed areas are limited to the region closer to the coastline and a few kilometres inland, where the present groundwater depth is low due to the water table lying close to the ground's surface and mean groundwater depth is expected to decline significantly, with likely consequences for superficial dependent systems (e.g. wells, lakes and river etc.,). Conversely, unexposed areas are those in which present groundwater depth is already too high to support superficial ecosystems and those in which mean groundwater depth is not expected to decline or is expected to raise.

Significant statistics were calculated for the considered future scenario focusing on each receptor, as reported in (Figure 5 appendix A. The table of Figure 5A shows the total exposed surface (Km^2) of each receptor in the five exposure classes and indicate the percentage of exposed surface of each receptor. By the table, it is evident that agricultural areas will have the largest total exposed surface (almost 3.7sq.km) distributed in all the exposure classes, while superficial water bodies, forests and semi-natural systems will have a smaller total exposed surfaces. The percentage of exposed surface, except for lakes, is around or lower than 5% of the total exposed surface of each receptor. Based on these data, the percentage of exposed surface within each exposure class has been depicted in Figure 5B. According to these statistics, the forest and semi-natural environments are projected to have nearly 70% of their total exposed surface associated to the very high and high exposure classes; superficial water bodies will have approximately 55% of their total exposed surface in the two higher exposure classes, while a little more of the 40% of agricultural areas' total exposed surface is included in the high and very high exposure classes.

Several statistics were calculated also for shallow wells, and these revealed a small percentage of exposed wells in the future scenario. In particular, less than 3.5% wells will be exposed to the GLV-related hazard.

Exposure maps were produced also for SI impact considering the four different seasons. These maps revealed similar exposure when comparing the same season in different scenarios. In this analysis, SI exposure map for the winter season and average scenario was selected since it shows the highest exposure.

Figure 6 presents the exposure map for the considered region showing potential limited exposure to the SI related hazard within the coastline (i.e. changes in saline interface depth will only be restricted to the coastal strip). Consequently, SI related impact might not bring serious threats to the considered receptors, which are not directly dependent on coastal groundwater aquifers, except few over utilized wells located along the coastline. For this reason, there are neither detailed analyses of exposure related to SI nor specific statistics calculated for the examined receptors. However, such outcomes agree with previous analyses (e.g. Alberti et al., 2009), regarding saltwater intrusion impacts in this region, which had foreseen significant annual variations in saltwater intrusion based on future climate change scenarios only at the coastal strip.

4.2 Susceptibility map

The susceptibility map presented in (Figure 7 appendix A) represents the considered receptors' sensitivity to GLV related impacts. According to this map, almost all agricultural areas and forests and semi-natural environments are classified with high and very high susceptibility scores, due to the prevalence, in the considered region, of permanent crops and annual/pasture/arable crops, which are characterized by high or very high susceptibility scores according to their water requirement. With regard to the susceptibility scores of forests and semi-natural environments, the final score is mainly due to the extension of forests, which are quite wide with a low level of fragmentation, while the vegetation cover typology, has a lower influence on the final susceptibility assessment.

Finally, the susceptibility scores for the superficial water bodies (e.g. Esino river and lakes) are quite heterogeneous, ranging from low to medium classes. The spatial distribution does not show the presence of hot spots (i.e. areas characterized by high susceptibility scores) or cold spots (i.e. areas characterized by very low susceptibility scores). The medium and high susceptibility scores assigned to wells is mainly due to the average volume of water extracted per year, and are distributed all over the considered region.

As far as the susceptibility to SI impact is concerned, Figure 8 in appendix A highlights that superficial water bodies located within the coastline, such as lakes and the Esino River, are characterized by medium to high susceptibility scores. This is due to the dynamic transition between unconfined coastal aquifer, seawater and surface water bodies and to the low average flow rate of the Esino River that would result in high susceptibility to saline contamination.

4.3 Risk map

Risk maps for the GLV impact for the considered receptors and areas, coherently with the exposure maps, have been focused on the summer season, according to the observation in section 4.1 and with the aim to analyse the extreme effects of a dry climate in the future scenarios.

The risk map presented in (Figure 9 appendix A) shows that areas at risk are concentrated only close to the Esino River mouth in a coastal strip of a few kilometres. Moreover, it emerges that agricultural areas are classified mainly in the three lower relative risk classes (i.e. from very low to medium). This is due to the exposure score, as the classification of susceptibility in that area was quite homogeneous. The other three receptors show a more homogeneous spatial distribution among the five relative risk classes.

Several statistics have been calculated related also to the relative risk assessment (Figure 10 appendix A). Looking at the total surface potentially at risk (km^2) of the considered receptors in each relative risk class (Figure 10A) and the related graph with the percentage of surface potentially at risk (Figure 10B), it is evident that agricultural areas are the less threatened receptor, with less than 4% of surface at risk, more than 80% of surface at risk classified within the three lower classes (i.e. from very low to medium) and less than 5% in the very high relative risk class. The other three receptors have a greater percentage of area at risk, though around 50% of their surfaces at risk in the three lower classes, while the surface percentage in the high and very high classes is quite different. Lakes and forests and semi-natural environments have around 20% of their surfaces at risk in the very high-risk class, while the same class for Esino River covers about 40% of its surface at risk.

To summarize, the analysed relative risk map and the related statistics show that GLV related impacts in the summer season would bring limited effects on the case study area, especially on agricultural areas.

Regarding shallow wells' risk assessment related to GLV impact, risk maps and related statistics for the future scenarios and seasons were not produced, considering the very small percentage of exposed wells in the case study area. Similarly, SI impacts risk analyses for the examined scenarios and seasons were not considered, due to the limited exposure of receptors to seawater intrusion within the coastal strip.

4.4 Damage map.

The damage maps for the GLV impact in the case study area were produced according to the procedure described in section 3.2.6. In correspondence to the exposure and risk assessment, the damage assessment was focused on the summer season of the average scenario. It considered the relative risk maps and the value maps, produced for different receptors in the case study area (Figure 11 appendix A).

Agricultural areas show values, which range from very low, close to the coastline, to very high, in the part of case study area far from the coastline. The value scores are given by the presence of high value of crop productions, and generally these are higher moving inland from the sea. The other receptors, instead, have usually more homogeneous value scores and are mainly classified in the lower value classes.

Based on these results, damage maps for the GLV impact have been produced with regard to all the considered receptors in the case study area. Accordingly, Figure 12 in appendix A depicts the damage map for the summer season of the average scenario. That map shows very limited or no damages for all the considered receptors, including areas close to the Esino River and lakes, which are projected to experience higher surface percentages in the very high risks class in the future scenario (i.e. summer season of the average year), as previously highlighted in section 4.3.

Overall, the damage analysis shows that changes in coastal groundwater levels due to the future predicted variations in the precipitation regimes and water table depth at seasonal scale, will likely have few consequences on surface water bodies (Lakes and Esino River) and on a large part of the natural systems and agricultural areas; because such most valuable receptors - according to value maps – are located where very low or null exposure is predicted.

5 CONCLUSIONS

The proposed spatially resolved RRA methodology is aimed at characterizing and prioritizing climate change related impacts and risks for coastal groundwater resources and dependent ecosystems in the lower Esino River valley, and thus identify areas that are likely to experience more consequences than others within this region.

Accordingly, this methodology considered outputs from a model chain that integrates an ensemble of climate, geomorphoclimatic and hydrogeologic models and downscaling techniques to model relevant climate variables at the global and sub-continental scales, in order to support future hazard scenarios construction at the basin scale. Based on such scenarios, the GLV and SI impacts were analysed through the assessment of exposure, susceptibility, and risk and damage.

Significant results that emerge from this analysis highlight how climate change could pose negative effects with different magnitudes and severity, appearing mainly as quantitative impacts (i.e. variations in groundwater levels impacts on dependent ecosystems) and less as qualitative ones (i.e. changes in saltwater interface depth impacts on coastal aquifer and dependent ecosystems). In particular, the results point out that seasonal variation in climate changes will affect the conditions of superficial water bodies and thus impede the availability of surface water for irrigation and other human purposes. This might potentially cause further stress on the Esino coastal aquifer, due to an increase of the water extraction demand.

Furthermore, the presented relative risk assessment methodology help to identify key aspects of coastal groundwater-surface water system interactions and together understand the spatial vulnerability of the regional coastal aquifer and its dependent ecosystems to potential seasonal changes in climate variables and anthropic pressures. In this regard, the presented analysis further underscores the need for investigating and monitoring coastal groundwater resources, to provide valid knowledge of environmental features and conditions needed to understand the dynamics of groundwater systems and to analyse effectively their complex issues, considering both short and long timeframe scenarios within an ecosystem approach. This would further reduce the level of uncertainty that often plagues climate change impact assessments and thus provide relevant information most needed for managers and planners’ adaptation practices.

On the whole, the analysis supports the sustainable management of coastal groundwater resources and its dependent ecosystems in the lower Esino River valley, by the means of relevant risk indicators useful to adapt current regional water managers’ planning and management strategies to future climate changes, in accordance to key principles of the WFD and Groundwater Directive.

Finally, the spatially resolved methodology applied with the GIS-based DESYCO tool, provides an effective environment for analyses and processing of large heterogeneous quantity of spatial environmental data. Thus, the analysis improves the flexibility and adaptability of the approach in terms of spatial and temporal scales. Further development of the presented methodology could consider the classification and normalization of vulnerability factors (i.e. susceptibility and value factors), which should be given in-depth consideration, e.g. using additional datasets and monitoring data, to improve the assessment of potential hazards and the spatial vulnerability of targets and areas to multiple stressors within the considered region.

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CHAPTER 5

The science-policy interface for climate change adaptation: the contribution of communities of practice (COP) theory

Iyalomhe F., Jensen, A., Critto A., Marcomini A (2013). Science-policy interface for climate change adaptation: the contribution of communities of practice theory (Accepted for publication in the international journal of Environmental policy and governance).

ABSTRACT

Climate change adaptation demands a successful science-policy interface that can enhance the translation of climate scenarios to adaptation policies. However, experience shows it is difficult to implement this interface in practice, particularly at the regional/ local scale. This paper considers the communities of practice theory in a new way, by examining two model cases to highlight aspects of potential opportunities for the theory and the disagreements between the theory and cases, and to understand how a successful science-policy interface in climate change adaptation projects could be envisioned as a community of practice. The assumption is that the social context in which these projects often exist could be established by the concepts of 'communities of practice,' which defines activities in a social and historical context that gives structure to the engagement of participants. We compiled cases from open-ended surveys and interactive research experience and observation, and inductively reflected on them vis-à-vis communities of practice. The model cases revealed challenges as well as opportunities for communities of practice. They exist within a middle space (social context) that could facilitate personal and professional relationships and promote formal and informal interactions that are needed to negotiate different expertise and narrow apparent boundaries. We conclude that vigorous and dynamic communities of practice promise to nurture the social context in which participants in adaptation projects are potentially engaged, and thus provide a provisional support to the science-policy interface.

Keywords: Communities of practice, climate change adaptation, science-policy interface, social context, Esino River Basin, Red River Delta

5.1 Introduction

Climate variability and climate change are undeniable risks to environmental ecosystems and their ecological functions, and yet they offer opportunities for adaptation i.e. the adjustment in the ecosystem's natural state and character in response to expected effects (Scheraga et al., 2003; IPCC, 2001). Ultimately, climate change adaptation is aimed at reducing climate related impacts and risks and taking advantage of emerging opportunities (Ziervogel and Zermoglio, 2009; Ziervogel et al., 2010). However, climate change adaptation is a multidimensional and dynamic process requiring informed decisions based on potential impacts of climate change, public perceptions, knowledge and experience (Scheraga et al., 2003; Lange and Garrelts, 2007; Adger et al., 2009; Ziervogel et al., 2010). Thus, decision-makers and managers are increasingly asking for improved climate science information in the development of all-inclusive environmental adaptation strategies i.e., including issues relating to social structures, economic and politics (Liu et al., 2008; Juntti et al., 2009; Dilling and Lemos, 2010) in order to produce positive changes.

As a result, the last two decades experienced a remarkable innovation in climate science, such as forecasts of changes in climate variables and impacts on ecosystems (McBean and Hengeveld, 2000; Leal Filho, 2009; Naustdalslid, 2011; Tribbia and Moser, 2008). Equally remarkable, in the worlds of science and of policy, is the growing understanding of the challenges and opportunities presented by such knowledge innovation. Ideally, environmental adaptation policies are developed through translating and applying natural and social science knowledge in light of the needs and human values of society (Bernabo, 1995). Thus, the need for translation of knowledge emerges as the worlds of science and of policy often appears to be mutually exclusive and unreceptive to each other (Van den Hove, 2007). For instance, the translation of global climate scenarios to regional and local scales where adaptation is most needed is still problematic, notwithstanding the assiduous efforts of the Intergovernmental Panel on Climate Change (IPCC) to make climate science clearer and relevant to decision-makers. Consequently, there seems an inconsistent relationship between scientists' knowledge and the knowledge demands and use of the end-users[1] or 'climate policy-makers'. Reflecting this inconsistent relationship, surprisingly, there is a dearth of studies that systematically examine just this (Liu et al., 2008; Jones and Jones, 2008). Climate change is often described as deeply rooted in society, and thus represents a new range of environmental problems that require revisiting the relationship between science, end-users and governance (Naustdalslid, 2011).

This relationship perspective supports the call for an in-depth consideration of the science-policy interface in order to highlight possible reasons why the interface falters and to tentatively suggest opportunities and approaches for successful relationships between knowledge production and policy formulation, especially concerning climate change adaptation. For this purpose, we consider the communities of practice theory in a new way, by examining two climate change adaptation model cases to understand how a successful science-policy interface in these cases could be envisioned as a community of practice. Next, we conduct a scope study to identify prevalent challenges confronting the science-policy interface, to better understand how to illustrate this interface in the climate change adaptation arena. In section 3, we propose the communities of practice concepts that demonstrate how these can succeed theoretically in facilitating and maintaining robust relations between researchers/experts and climate policy-makers, while in section 4, we examine the two climate change adaptation model cases, one in Italy and one in Vietnam. Finally, we discuss them vis-à-vis community of practice theory.

5.2 Science and policy interface: constraints and challenges

Bridging the gap between science and policy is a daunting task[2], considering the blurry boundary between the worlds of science and policy as established by a range of studies (e.g. Cash et al., 2006 and 2003; Van den Hove, 2007; Janse, 2008; Holmes and Clark, 2008; Weichselgartner and Kasperson, 2010; Vogel et al., 2007; Slob et al., 2007; Magnuszewski et al., 2010; Ziervogel et al., 2010; Kasperson and Berberian, 2011). A multitude of studies have attributed the connection between knowledge development and policy formulation to several factors that often intersect and influence the interactions of science and policy. According to Naustdalslid (2011), Leal Filho (2009), Dilling and Lemos (2010), the misconception of climate change by both the science and policy worlds exclude climate information from relevant policy arenas, and thus create two parallel efforts aimed at the same problem. In addition, policy makers have perceived climate related issues to demand a progression of technological innovation rather than better policy formulation. Thus, they are hesitant in interacting with scientists and in accepting ownership of relevant climate information. McBean and Hengeveld (2000) stress that among scientists much emphasis has been placed on issues of disagreement rather than agreement i.e. preventing proper communication of undisputed science therefore widening the gap between climate scientists and end-users. Parallel to this, Jones and Jones (2008) stress that the science and policy disconnection is also related to different accountability in the two worlds; scientists answer to scientific norms, methodological standards, research agendas and research funders while policy-makers answer to their constituencies, stakeholders, political agreements and political leadership/parties.

Numerous studies, e.g. Grundmann (2007); Dilling and Lemos (2010); Coelho and Costa (2010); McBean and Hengeveld (2000); Turnpenny et al., (2008); Dessai et al., (2009); Paavola et al., (2009) emphasize the difference in and intertwined nature of complex institutional settings and interdisciplinary norms that correlate to formal and informal decision practices. Policy, respectively, complicates their relationship and distorts input from science into policy-making. For example, policy-makers may reject climate forecast information in favour of tested adaptation practice, if and when political incentives are amplified, or there is perceived lack of tools and technical know-how to implement policy actions suggested by climate science, thwarting efforts to bring science and policy together. Moreover, according to Jacobs et al., (2005), inter-disciplinary complexity reflects adherence to different forms of 'jargons' and caveats within the science and policy worlds. This hampers effective communication and collaboration of actors and transfer of perspectives from science to policy. Dilling and Lemos (2010); Lemos and Rood (2010); Juntti et al., (2009); Linstead et al., (2010); Liu et al., (2008) support how this may lead to lack of understanding and credibility of climate forecast, and climate impacts assessment that are often obscured with uncertainty and ambiguous language evident in recent scientific studies. Such mismatch in communication of knowledge/information may result in climate adaptation policies that fall short of existing relevant climate knowledge and, significantly, lead to a questioning of the perceived authority and credibility of actors (i.e. climate scientists and policy makers). While Stephens et al. (2012) promotes that the non collaboration of science and policy is due to the imbalance between three communication imperatives of saliency for different user groups (interpretability and usefulness of the communication to a particular user), information richness (amount of information communicated), and adequate representation of robustness (the fidelity of the science and the degree to which this is communicated).

Conversely, Rayner et al. (2005) discovered that the relationship between climate scientists and decision-makers (regional water mangers) is constrained because regional climate forecasts are not institutionalized into water management and regulatory standards. In their study, this disconnection does not facilitate usage and thus, discourages experts and managers from coming together on issues of water resources management. Additionally, Janse (2008) stresses that natural scientists adhere to a myth of objective, value-free research, and thus prefer technical solutions, scientific rationality and methods as favoured logic. This mode of operating as knowledge producers not only reflects scientists' reluctance to compromise their culture but also mirrors an unwillingness to accept the subjective, value judgement and political rationality of policy-makers. Similarly, Benabo (1995); Cash and Clark, (2001); Weichselgartner and Kasperson (2010) draw attention to curiosity-driven research agendas, which may lead to science that does not respond adequately to policy relevant questions but diverges from these in scope, objective and priorities. Thus, it is difficult for science to meet the expectations of policy-makers, since scientists face difficulties in relating effectively with policy-makers within the research portfolio.

Furthermore, Pullin et al. (2009) underscore the reductionist approach, considered by many scientists to represent complex physical observations in simpler theoretical terms. McNie (2008) posited that this approach often results in a mismatch between specific questions addressed by science and the broad issues addressed by policy. Jones and Jones (2008); Jones et al., (2009); Vogel et al., (2007); Dilling and Lemos (2010) argue that a major mismatch between climate science and adaptation policy might be related to the time frame and scale of scientific research relative to policy priorities. In particular, policy-makers prefer immediate actions and regional/local information, and likewise, scientists' long timeframe for producing research-based knowledge leads to the lack of interaction between science and policy. McNie (2008) points to another mismatch that stems from the fact that scientist' rewards are mostly based on research publications in scientific journals but not necessarily on producing information that is considered as useful and relevant by decision-makers to handle pressing problems. Significantly, Feldman and Ingram (2009); Holmes and Clark (2008); Cash et al., (2006); Jacobs et al., (2005); Cash and Clark, (2001); Jones et al., (1999); Dilling and Lemos, (2010); Stephens et al. (2012) emphasise the non-consideration of relevant climate services, which could facilitate the production of usable science through adequate communication of saliency, credibility and legitimacy, in order to enhance the link between science and policy. They claim this as a major reason for weak collaboration between the worlds of science and policy and for lack of established adaptive management of climate impacts on human society.

Overall, the literature we reviewed conceptualizes the science-policy interface as ambiguous, due to different institutions and heterogeneous paradigms in the science and policy worlds. Moreover, the studies suggested a gap between climate researchers and climate policy-makers, mainly because of a limited ability to comprehend climate change complexity and its interactions with society and political structures and processes. Nevertheless, across most of the literature, the relationship between the world of climate science and the world of climate adaptation policy is considered a vital potential mechanism for successful interaction aimed at climate change adaptation.

Three distinct issues emerged from the literature (e.g. Weichselgartner & Kasperson, 2010): (1) structural aspects, e.g., organisational settings or complex institutions and standards; (2) functional aspects, e.g., tested practice, objectives and needs, procedures and scope and priorities, and (3) social aspects, e.g., cultural values, communication, understanding, social networks and uncertainty. This suggests we view science and policy as separate complex entities with different modus operandi, marked by dynamics operating through habits and routines that do not favour varied interactions and relationships. Concurrently, other studies, including Kasperson and Berberian (2011) and Vogel et al. (2007), argue that the worlds of science and policy do engage and their engagement should be seen as (institutional) actors located in a complex spider-web of connectivity and exchange, in which link and interactions between groups ensure that knowledge and practice are contested, co-produced and reflected upon. This line of arguing describes the science-policy interface as a complex multi-level system of control and of knowledge production among a group of actors engaged in knowing and managing crucial environmental issues (Cash et al., 2006; Vogel et al., 2007). However, while the importance of involving all actors in transient relationships is highlighted, a detailed understanding of the social context required for fostering robust relationships and trust is lacking. Hence, the community of practice approach has not yet been applied to the science-policy interface, especially in the area of climate change.

5.3 Communities of practice (COP) theory

According to Wenger et al. (2002), communities of practice is a “group of people who share a concern, a set of problems, or a passion about a subject matter, and who deepen their knowledge and expertise in this by interacting on an on going basis”. We present the theory based on its three characterising concepts: joint enterprise, community and shared practice relevant for the structure of a social action and relations. Originally, Lave and Wenger (1991) proposed the theory of communities of practice to conceptualize learning within social settings and also as a “new approach” to knowledge sharing and creation enveloped in complex social networks aimed at addressing a common problem.

5.3.1 concepts and mechanisms

'Joint enterprise' denotes the shared pool of knowledge that serves a basis for the community members when they define and develop activities (Henry, 2012). It is these activities that help members to identify with the themes to be advanced by the community of practice. During participation in these activities, members derive purpose and establish values promoting the knowledge pool and build their identities. Moreover, the joint enterprise encourages members to contribute to the dynamic development of the community, through activities that not only give meaning to their actions but also emphasize and reflect their commitment to the joint enterprise (Wenger et al., 2002). Here, the knowledge pool is contextual (i.e. to handle climate change in watershed) and involves interdisciplinary and trans-disciplinary spheres where participants are expected to define the objectives, tasks and undertakings based on a communal mutual accountability.

The 'Community' defines the particular cohesive relationships and interactions among members. Communities operate within a social system where healthy relationships are defined and fine-tuned in the interactions (Wenger, 1998). Repeatedly, these communities are based on mutual interaction of members within a social space, in which activities carried out help to define and deepen collaboration that serve as reference for members' (professional) identities and help them develop the necessary mutual atmosphere of trust. These community activities are largely influenced by quality interactions and relationships that in the view of several studies (e.g. Zboralski, 2009) often are defined by interpersonal trust and cohesion between members, the types of communication and the frequency of interactions. These activities enable communities' members to utilize the potential of the communities by being able to ascertain each other's competences and abilities to contribute to developing the joint enterprise. Significantly, communities of practice never exist in a vacuum; multiple relationships and a jointly negotiated enterprise are needed for communities of practice to be meaningful and structured and for the development of a common frame of interpretation.

The 'shared practice' refers not only to routinized activities defined by members that evolve mainly from their collaboration. The notion also refers to common procedures or know-how jointly developed and situated within the community (Henry, 2012). Common practices also cover the physical demonstration of experiences and expertise shared by members, which become reified as the way to do things and to produce contextual knowledge over time (Wenger et al., 2002). Thus, common practices often develop as specific knowledge matures through the interaction of competence and experience, maintained and shared within mutual engagement over a period of time (Madsen and Noe, 2012). For example, communities of practice may develop norms in the form of codified procedure, language, well-defined roles, specified criteria, tools, actions and documents, etc. In our perspective, these not only envelope the shared and created knowledge (practice) but also reflect the defined relationships that exist between members. In this way, communities of practice grow out of members' common interest and concern and help them develop relationships that interlink competences and experiences (or reifications) through shared practice.

Clearly, these concepts become intertwined and redefine one another as the community develops. Thus the joint enterprise largely indicates the kind of relationships and mutual accountability that evolves and the shared practice that is developed in the doing. Consequently, communities of practice present a more viable model for a strong social structure in the science-policy interface than other participation approaches (e.g. two-way interaction model), often characterized by boundary organisations that prevent actors from establishing direct participation useful to swap their traditional roles (Vogel et al., 2007; Cash et al., 2006). In this perspective, we argue that the community of practice approach potentially supports relationships vital for research projects to ultimately achieve competence needed for the defined objectives. Therefore it denotes a social space in which relationships are based on participation and continuous interaction of actors with diverse expertise around common themes and interests, in order to develop a historically based contextual knowledge or what Lave and Wenger called shared practice (Wenger, 1998; 2000). At the core of communities of practice lie historically and socially shared forms of knowledge and relationships, which do not exist in related epistemic communities also built around a common objective. Communities of practice also negotiate how the jointly accepted knowledge is perceived as useful, by bringing together a bank of expertise within which it is possible to include unique knowledge relevant for accomplishment of objectives and development of strategies and policies to, for example, adapt to climate changes. Consequently it signifies a social platform for easy communication and learning between knowledge producers and users, which may include actions to examine, address and negotiate solutions to pressing problems (Hearn, 2009). Accordingly, communities of practice potentially allow interactions among different perspectives of knowledge on issues linked to societal adaptation to climate-related problems, by enhancing and serving as platforms for natural sharing of knowledge, communication and interpretations to include the users' specific needs. This not only makes communities of practice an appropriate arena for evidence-based policy-making but also for building and maintaining social trust (i.e.

coherence) that may be established when continuous interactions and relationships potentially evolve through active participation and mutual engagement in joint processes. Such relationships can help to exchange the traditional roles of both science and policy worlds, thus allowing joint interpretative frameworks and a shared understanding of climate adaptation in specific adaptive learning projects.

5.3.2 Communities of practice and project organisation

Communities of practice thus present a promising approach to establish the social context in which projects-based activities and analyses can evolve. For climate adaptation projects, these activities take place in formalised organisations, which do not constitute communities of practice per se. The difference between the two notably concerns the roles that actors play in communities of practice and in project organisations, respectively. 'Members' of communities of practice are not formally assigned specific roles and the more informal roles, which members adopt, are not defined with respect to the organisation's enterprise (Probst and Borzillo, 2008). In contrast, as Bettiol and Sedita (2011) argue, project organisations often develop separately and are concerned with the achievement of specific objectives - partners with different tasks are linked to these objectives. Additionally, project organisations have clear boundaries kept together by research goals, milestones and deliverables, and have a prearranged schedule of completion. Communities of practice evolve more ad hoc, according to the development of contextual-knowledge and activities. However, communities of practice have a strong potential to emerge or be maintained in project organizations. Newly created networks and bonds are sustained when a common purpose of advancing a particular field of knowledge exists, e.g. the vulnerability and adaptation of socio-ecological systems to climate change. When also developing shared and knowledge-based practices, such networks and bonds around knowledge and action may evolve into a community of practice. Members of the communities of practice thus include both actors from the formalized organization and actors from other social and professional settings. Project partners may, for example, experience problems beyond their competences, and this might move them to interact with others in the development of new competencies demanded by these problems. Equally, in the quest to solve a particular problem, research group members may engage in a community of practice, where they can deepen their knowledge and experiences towards a particular knowledge domain (Wenger, 1998; Roberts, 2006; Meeuwesen and Berends, 2007; Lave and Wenger, 1991). Accordingly, Fig. 1 shows idealised science-policy links within a research project-based community of practice. Here we suggest that various direct two-way interactions between experts/scientists and climate policy-makers/stakeholders subsist in which there exists a high degree of engagement, negotiations, reflections and feedback. Kasperson and Berberian (2011) and Vogel et al. (2007) follow the same line of argument with what they have termed complex and stable connections between science and policy. In our case, these vital connections are envisioned as community of practice where the boundaries between involved actors' are blurred and 'doing' is central, either as highly engaged (i.e. between core members) or less engaged (i.e. involves peripheral members), both in consideration of relevant expertise and competencies, leading us to examine the concepts of communities of practice theory vis-à-vis climate change adaptation projects, to identify aspects that converge with the theory and those that conflict, and thus facilitate the understanding of how a successful science-policy interface in these projects might be envisioned.

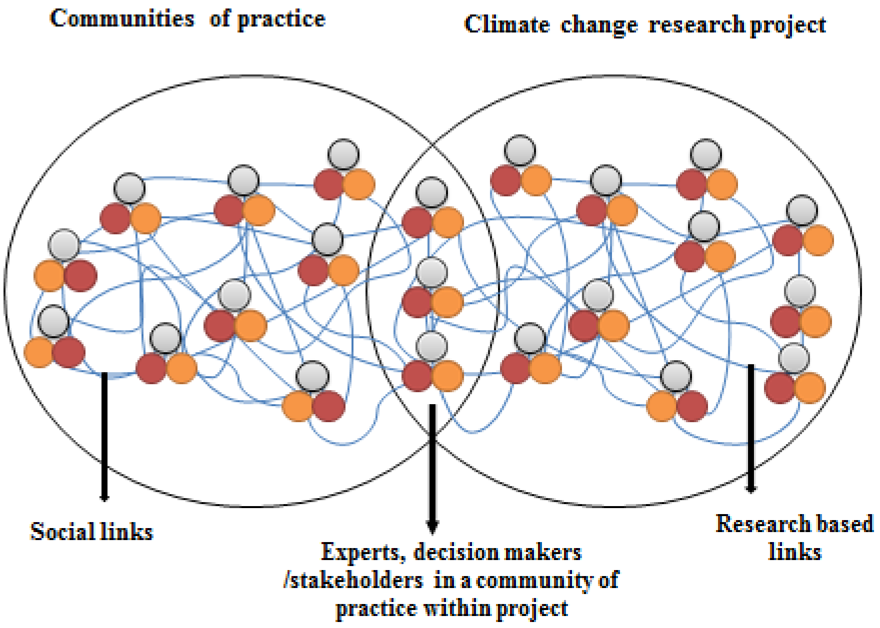

Fig.5.3.2. A hypothetical representation of linkage between experts, decision-makers/stakeholders within research project-based communities of practice

5.4 Materials and methods

We use open-ended surveys, interactive research experience and observation to describe the climate change adaptation projects. This gave us diverse views of experiences of project partners and the context in which the projects were organised. These projects were chosen based on the research agenda (i.e. climate change adaptation) aimed at different spatial scales, which provide different perspectives and outcomes that suit the projects' roles in this study as model cases. Our analysis was inductive, i.e. we allowed important concepts and aspects to emerge during reflection on the model cases rather than in advance. This approach is ideal to exploratory studies and thus allows us to examine these cases in their different broad contexts. First, the European case is located in the Esino River Basin in Italy, which focused on groundwater resources management and the second was located in a more research-led project in the Red River Delta in Vietnam, focused on changes in livelihoods due to transformations in water flows and altered water management.

5.4.1 Esino River Basin case

The EU Life project- SALT[3] was aimed at contributing to the efficient use and protection from saltwater intrusion of groundwater resources in the lower Esino river valley in the Marche region. Significantly, SALT was conducted within the period (2009-2011) as a pilot project intended to create a model for the implementation of two EU policies[4]. For this purpose, the project included a consortium of scientists from several institutions of higher education, including the Universities of Venice and Ancona, the Polytechnic of Marche, consultants in the fields of environmental engineering and the sustainability integrated water supply and management, and local and regional stakeholders. Stakeholder engagement was based on their undertakings and experiences with respect to the river basin, thought helpful for validation of the jointly defined integrated assessment framework and for operative teamwork during the project activities. The assessment framework allowed inclusion of expertise originating from different disciplinary (scientific) backgrounds, including climatology, hydrology and hydrogeology, information technology, and social sciences, as well as practical expertise from relevant stakeholders, such as regional environmental protection agencies, municipalities, regional river basin authorities and industrial and agricultural authorities, etc. The integration of this range of disciplines within the assessment framework offers a section of all the scientific backgrounds coming together to jointly define a contextual knowledge domain, and to create procedural norms and management strategies, based on different perspectives of knowledge and practical know-how from the local stakeholders.

SALT activities were organised in ten work packages - each assigned to consortium partners (or research groups), except Multiservizi SpA[5,] which acted both as project coordinator and as a mediator between experts and local stakeholders. Other research groups' activities were contextually focused in order for them to vividly identify relevant and valid knowledge through systematic approach of data collection and analysis in relation to the river basin natural phenomena, and modelling of biophysical and hydrogeological processes, and the development and application of a management support tools (Life+, 2011).

The huge heterogeneous data collection and analysis carried out by research groups led to valuable participation and teamwork i.e., experts and researchers, on the one hand, and experts and stakeholders, on the other. This led to the joint development of a GIS database system employed to collect and organize data (e.g. data on stream flows, salinization and groundwater levels) through active contributions of scientific experts and managers. From the application of the GIS database emerged a shared practice for watershed assessment and management with respect to climate change issues. Moreover, relevant data and information useful for partners' specific tasks were also shared during formal and informal meetings, conferences and technical workshops. Activities within the research groups included formal and informal interactions (i.e. co-analysis and co-results production), through which continuous interactions were gradually sustained by building commitments and personal acquaintances. Furthermore, these interactions prompted quality relationships and collaboration geared towards the specific tasks of each group. Within the mixed research groups, knowledge was trans-disciplinary and participation premised on active engagement in activities. This form of knowledge network related activities does more than stimulate learning and acquisition of new skills among members in the doing. These activities further facilitated personal and professional relationships among members, based on established confidence through teamwork that led to early completion of tasks.

Conversely, interactions between project partners or research groups was only limited to data and information sharing, aimed at supporting the completion of the groups' tasks, and not at developing new joint knowledge for the groups, or at group members acquiring new competences and expertise. Significantly, project partners reported consistently that the inter-research group' activities of data and information sharing were not accomplished with a high level of commitment compared to what happened within the research groups, perhaps due to variations in research groups' specific task and knowledge perspective. Nevertheless, inter-research groups' interactions were based on e-mails, telephone and fax, and in some cases formal meetings or workshops meant to reflect on the overall project objectives and examine the progress of partners through discussion of their results. The interactions existing between experts and stakeholders were not extremely structured, compared to that of scientists and experts alone, because the assessment framework defined-activities do not facilitate the involvement and consideration of stakeholders and their practical knowledge, except in the understanding of how climate change historically has influenced the entire watershed, e.g. river basin surface and groundwater availability (Life+, 2011).

Consequently, relevant results of the SALT project reflect that the assessment framework defined-activities and the contributions of experts and stakeholders in the developed knowledge network are significant for achieving joint objectives. However, variations were present in the specific activities and objectives of experts and stakeholders or in the formal organization of activities among experts and stakeholders, particularly prominent in their primary interests in the project development. Stakeholders were primarily interested in climate change effects on water availability as this affected their business, while consortium experts were concerned with the methodological aspects and improvement of tools in order to enhance the understanding of how climate change influenced and would influence the river basin water resources (SALT deliverable, 2012).

5.4.2 Red River Delta case

The Red River Delta case, funded by the Danish development agency, DANIDA, was conducted as applied research in collaboration with Vietnam National University (VNU), Vietnam; and Aarhus University (AU), Denmark. The project- ClimLandLiveDelta was conducted within the period (2010- 2012) to addressed two parallel and intertwined questions: how do climate changes alter the water flows of the Red River Delta and what impact does this have for local agriculture. Additionally, how does this climate impact change the conditions for livelihoods in four local areas? Meanwhile, the Vietnamese government worked to develop a national adaptation strategy and requested information on, as well as instruments to instigate profound societal changes. The project was organised around research leading to policy recommendations, and the project partners consisted of a project management at VNU and key natural and social scientists at both VNU and AU, while local, regional and national stakeholders and policy-makers were formally and especially informally connected to the project.

Close connections with local and regional level policy-makers were necessary in order to gain access to the selected areas- located in communes. In addition, access to local people, to testing sites and to local decision-makers was dependent on trusted and personal connections between the Vietnamese research team and the political and local leadership. The researcher in charge throughout the project sustained the research network, fostered by shared lunches and presentations, also including national policy-makers and leadership, which provided the basis for collaborations among partners of the project and decision-makers. Furthermore, such personal relationships also allowed for researchers to present preliminary results to policy-makers, while these interactions provided the policy-makers with arenas for discussing mid-way results and requesting that specific areas of climate change adaptation be covered.

Networking did not, however, evolve around knowledge-producing practices developed within the project. Rather, the knowledge practices were research driven and developed along two tracks. Firstly, the project resulted in the refinement and adaptation of water flow model and the soil and water assessment tool (SWAT), originally proposed by the Danish team to conditions in the Red River Delta through e.g. integration of satellite data and GIS-mapping introduced by the Vietnamese team of researchers. These network activities make the role of local and regional stakeholders and policy-makers more indirect, as these partners, on the one hand provided access to the vital information on changing geographical conditions in the delta, and on the other, were able to connect this to social and livelihood changes in the case areas. Secondly, the social science team applied a combination of questionnaire and qualitative interviews with an extensive number of households in the case areas. Both interviews and the questionnaire depended on the active involvement of not only local residents of the households but also on the training and engagement of assistants to cover the large number of households. Through discussions within the group of social science researchers and among researchers and interviewees and through the interviews, the residents and the research team could jointly pinpoint the key areas of change on livelihoods.

Thus, the SWAT model and the analytical framework behind the questionnaire and the interviews provided a knowledge domain developed in collaboration with the researchers and climate policy-makers/stakeholders, which encouraged practices as well as capacity building at local and university level. Also, the building and maintaining social networks among researchers, policy-makers and stakeholders played a crucial role in the project, through policy-makers engaged in developing Vietnam's national adaptation strategy. Instruments were more distanced, although the regional and local policy-makers of communes were not directly involved in designing or implementing climate adaptation initiatives. While the project did include the features of a community of practice, the bridge between science and policy, perhaps of later significance, this was not strong during the project period.

5.5. Communities of practice in climate change adaptation projects: opportunities and contentions

We discuss communities of practice in a perspective placing the social context of climate adaptation projects at the centre. This social context potentially promotes and sustains mutual engagement and the negotiation crucial for the inclusion of scientific knowledge into the definition of shared-ways of practice (repertoire) in these projects, and for joint problem solving that engages researchers/experts and (climate) policy-makers/stakeholders. In this way, we have presented the social context as an arena where continuous interactions and relationships are premised on participation, commitment and on the trust.

The understanding and management of processes and interactions, which occur in the boundary between partners engaged in the model cases, thereby suggests as a promising way to narrow the gap between science and policy, and also to deal with the complexity of different knowledge perspectives required by climate change adaptation policies. This mirrors other findings (e.g. Vogel et al., 2007; Hegger et al., 2011) and practices. Moreover, the science-policy interface that exists within the model cases proved a significant arena for development of both general and contextual knowledge and capabilities, with substantial potential for improving environmental management and governance. However, its context determines how this is achieved. As a main feature, this interface encompasses interactions and relationships between various scientists, policy-makers, managers and local stakeholders through collaboration in sharing, production and application of knowledge (Van den Hove, 2007). In communities of practice theory, the potential is increased for this kind of collaboration and engagement, aimed at what Lave and Wenger, (1991) called ‘mutual learning’ and creation of jointly accepted knowledge. The defining feature being that here engagement between researchers/experts and policy-makers/stakeholders in the community is based on actual participation that refers to both action and connection, built and maintained through negotiation, reflection and feedback with the aim to better understand, in our case, climate change adaptation and to inform related policy-making.

Therefore, we suggest that this particular nature of the interface may be as influential on policymaking as is the scientific knowledge. Premised on the exploration of the concept of communities of practice as a feasible way to approach climate change adaptation, our analysis indicates vigorous and dynamic communities of practice may bridge the gap often evident between science and policy in the management of climate change problems (Naustdalslid, 2011), including its diverse stakeholders’ interest (Jacobs et al., 2005). For example, the problem of each side having a different language, or different rewards structure, the community of practice gets around this by giving a focus to a joint enterprise and participation, with an outcome in practice being the reward. The proposed concepts of communities of practice promises to support the development of the social context in which climate change adaptation projects often exist, in that its revolves around three main concepts: joint enterprise, community and shared practice that mutually provide meaning to participation and the mutual knowledge sharing and creation. Significantly, this social context is embodied in the negotiation of practice, directly affecting the behaviours and abilities of members, relying strongly on the interplay between participation and reification. This allowed our model representative cases to tackle the issues of interest common for the formal and informal participants, offering expertise from different disciplines as well as practical know-how from stakeholders. Within these cases, researchers/experts and policy-makers/stakeholders had different interests and understandings, but were able to create an arena in which their expertise and different forms of knowledge could convene and at times intertwine to a common goal.

The framing and procedure of common issues and problems were largely expressed in the integrated assessment framework (i.e. SALT project) and a survey/interview framework/the SWAT model (i.e. ClimLandLiveDelta project), which suggests the creation of a 'middle space' as discussed by Kasperson and Berberian, (2011). In this middle space, researchers/experts and policy-makers/stakeholders intersect and their different expertise and experiences potentially merge or communicate, creating a joint and valid contextual knowledge, relevant to address the watershed problems. In the SALT case, the middle space included the formal and informal interactions proven quite asymmetrical, enabling the involved scientists, policy-makers and stakeholders to negotiate their different expertise, while the differences in expertise often were anticipated as barriers for joint learning and joint knowledge production. However, participants were able to narrow their apparent boundaries in order to enhance co-analysis and co-production of results. In the Red River Delta case, relationships of experts and stakeholders within the middle space were gradually built over time but the level of personal engagement showed incremental change creating unstable social networks.

Both the cases and the mixed experiences indicate how the form of collaboration facilitated personal and professional relationships among members based on established trust through participation. And further that, this helped to build and sustain community-based network in which researchers/experts operate within research projects with stated policy relevance. Additionally, the informal and limited engagement of local and regional stakeholders improved the production of a community-kind of shared knowledge repertoire, which potentially encourages jointly defined practice in a longer perspective. For example, researchers and stakeholders in the model cases applied the jointly developed GIS database to implement water flow, climate and hydrogeological and risk models, to provide relevant mechanisms for national and regional adaptation strategies in Vietnam and Italy respectively.

Obviously, there are aspects of our model cases that conflict with a community of practice theory and thus undermine the original framework presented by Lave and Wenger, (1991). Among these is the participation of regional managers and local stakeholders in the projects' activities, which do not reflect continuous interactions of researchers/experts and policy-makers/stakeholders, except when there are obvious needs for practical data and information as reference for scientific framing of climate change adaptation analyses. Rather than undermining the focus of communities of practice on participation in social networks and practices as basis for mutual learning, sharing and co-production of knowledge, this suggests that the participatory aspect needs to be refined and adapted to the multi-actor setting of current climate adaptation policies where networks may move dynamically between fluent and more stable boundaries. In some sense, this challenges Wenger's (1998) view of legitimate participation, by discouraging the active participation of managers and local stakeholders in the development cycle of procedures and management tools. Suggesting a focus on methods for creating participatory practices may be useful. In addition, a strong focus on formal objectives (i.e. overall project aims) compared to informal objectives (i.e. individual project partners gain) affects the learning aspects of social practices, strongly stressed by Lave and Wenger, (1991). The cases suggest that strong emphasis on such formal objectives may hinder experts/researchers from personal exploitation of available knowledge and experiences (either as reification or shared practice). The production of a more ad hoc practice to meet these cases' primary objectives and perspectives in the short term did however also oppose the longer perspective, encompassing the more stable shared practices, emphasized within communities of practice as a product of active participation.

5.6 CONCLUSIONS

We have attempted to relate two fields of study by exploring the science-policy interface in climate adaptation projects and how the communities of practice theory might offer a new way to support the social context in these projects. For our purposes, two model cases described according to observation, interactive research experience and open-ended surveys, were inductively analysed, in order to highlight opportunities for potential communities of practice and to understand how this theory could enhance or inhibit a successful science policy interaction.

The model cases revealed challenges for communities of practice in the following aspects: a limited participation of stakeholders, much emphasis on formal projects' objectives than informal objectives, and the more ad hoc jointly developed shared-ways of practice. These cases also revealed several salient opportunities for the theory. They exist within a middle space (social context) that facilitated personal and professional acquaintances, based on established trust among participants, including formal and informal interactions/relationships needed to negotiate different expertise and narrow apparent boundaries, and can enhance co-analysis and co-production of contextual knowledge, relevant to address the watershed problems.

Thus, this kind of social context promises to nurture robust mutual engagement between researchers/experts and policy-makers/stakeholders in the climate change adaptation arena, specifically through focus on the locally developed shared-ways of doing as social processes and practices. This allowed us to envision the science-policy interface as vigorous and dynamic communities of practice for multiple relations necessary to tackle relevant practical problems in the era of global change, where solutions (involving complex policy process and societal values) largely depend on the nature of the social arenas in which these problems are often defined.

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NOTES

1. In this paper, ‘end-users’ refers to policy-makers, decision-makers, stakeholders and/or managers who consider climate research knowledge to be relevant inputs in climate policy formulation and decision-making, and who further consider climate change studies to be a relevant means to support their day-to-day management and planning aimed at reduction of vulnerability and enhanced adaptation (Mastrandrea et al. 2010; Weichselgartner & Kasperson 2010; Kasperson and Berberian, 2011).
2. Even though there is evidence that they are sometimes well connected, the opposite is also apparent (Slob et al., 2007)
3. Sustainable mAnagement of esino river basin and coastaL aquifers to prevent saline intrusion in consideration of climaTe change)
4. Water Framework Directive (WFD), and Groundwater Directive
5. Joint-stock company concerned with regional water supply

5.7 REFERENCE

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CHAPTER 6

6.1 CONCLUSIONS

This dissertation examines current DSS related approaches applied to the study of climate change impacts on coastal systems. It evaluates potential climate change related impacts and consequent risks for coastal groundwater-dependent ecosystems and also proposes a new approach to the science-policy interface aimed at climate change adaptation. In this context, the dissertation applies an ecosystem-based relative risk model to prioritize potential climate change impacts and risks for the Esino River coastal aquifer and its dependent ecosystems and reflects on a community of practice model to understand how dynamic and vigorous communities of practice promise to facilitate and nurture successful relationships between science and policy in the climate change adaptation arena. Accordingly, this work constitutes three research papers that have been presented in Chapter 2, Chapter 4 and Chapter 5, corresponding to the specific objectives set out earlier in Chapter 1. This final chapter provides a snapshot of the main findings of the three research papers, points out the limitations of the present study, and outlines ideas for future study.

The first research paper revealed that none of the examined DSS related approaches possess all of the relevant functionalities needed for both the assessment and management of coastal issues caused by climate change. However, a few of the DSSs, particularly DESYCO appear to supports dynamic analysis of coastal processes, prediction of scenarios' effects, integrated analysis of impacts via the inclusion of several models and datasets, and make complex information understandable through visualisation techniques (i.e. GIS, 2D, and 3D modelling). This analysis (i.e. Knowledge-based) highlighted significant functionalities and mechanisms that these DSSs provided for the support of the assessment and management of climate change related issues and thus serves as a guideline to potential readers or users in the selection of a DSS tailored to their specific needs.

In the second research paper, a relative risk model was applied within the proposed steps of the spatially resolved RRA methodology, to evaluate and prioritize areas and targets that are likely to be more affected by climate related risks than others in the Esino River basin. The proposed steps were applied to the lower Esino River valley to analyze GLV and SI impacts, considering relevant datasets, parameters, and techniques useful in producing GIS-based maps. The spatially resolved methodology was developed as a means of significant information needed to establish priorities for intervention and support the sustainable planning and management of coastal groundwater resources within the Esino River Basin. Accordingly, specific exposure maps of GLV and SI impacts were produced, alongside risk and damage maps of considered areas and receptors/targets.

According to the GIS maps and related statistics calculated for the lower Esino River valley with reference to GLV and SI impacts, the following emerged as significant findings:

1. There will be similar exposure to GLV impacts in the future scenarios and slight differences between the seasons (winter, spring, autumn and summer). Thus, the analysis was focused specifically on the average scenario with reference to summer in order to highlight possible extreme effects from climate change during the drought period. The results revealed significant variations in exposure for receptors/targets to GLV impact, particularly for the superficial water bodies (Esino River and lakes) and natural systems (i.e. forests and semi-natural environments), whose exposure in the very high and high exposure classes exceeds other receptors;
2. Agricultural areas will have the largest total surface exposed to GLV impacts, but most of this surface will be distributed within the three lower exposure classes (e.g. very low, low and medium);
3. A small percentage of the 4000 wells located in the lower Esino River valley, mostly around the lower part of the Esino River would be exposed to GLV impact in the future scenarios with reference seasons;
4. As far as SI impact is concerned, exposure will be restricted to the coastal strip. This implies no severe risk of saltwater intrusion and damages for the considered receptors/targets in the future scenarios and seasons.

The assessment of exposure, risk and damage in the lower Esino River valley according to the future climate change scenarios and seasons highlighted significant insights. First, it can be noted that SI and GLV impacts will affect the Esino River basin and related receptors in very different ways. The GLV impact will potentially affect superficial water bodies located in the lower part of Esino basin within several kilometers of the coastline, while SI impact will be restricted to the coastline or river mouth. Evidently, these first-cut results show the sensitivity of the Esino River hydro-geological system to climate change-induced variations in the water cycle. This could result in variations in groundwater recharge processes and lowering of the water table in the river basin. Hence, according to the investigated scenarios and seasons, climate change related consequences on the Esino River basin are shown to be less severe and not prone to worsening in the future. This understanding provides guidelines for addressing issues related to policies, management practices, and interventions, which need to be planned in advance and based on relevant scientific results. Still, the results highlighted that future consequences of climate variability and change are not easily predicted or assumed, without considering possible sources of uncertainty that are inherent with climate change impacts assessments.

The third research paper attempted to relate two fields of study by exploring the science-policy interface in climate adaptation projects and how the communities of practice model might offer a new way to support the social structure within these projects. The actors involved in climate change adaptation are being burdened with knowledge application rather than the creation of knowledge. As a result, the relationships/interactions of actors in interdisciplinary adaptation projects has become a crucial factor in the definition of successful adaptation strategies to climate change. This is because successful interaction can take responsibility for fostering knowledge sharing and the development and management of knowledge and competence. This interaction is simply a valuable mechanism to be reconsidered in an age when almost every field is dynamic and is affected by complex problems requiring multiple perspectives. In view of this, two regional climate change adaptation projects identified as model cases were described according to observation, interactive research experience and an open-ended surveys. These model cases were inductively analysed, to highlight opportunities for potential communities of practice as well as to understand how this might be an effective approach to successful science and policy interaction.

The cases revealed several salient opportunities for communities of practice. They exist within a middle space (social context) that facilitated personal and professional relationships, build on established trust among participants, including formal and informal interactions needed to negotiate different expertise and narrow apparent boundaries to enhance co-analysis and co-production of contextual knowledge relevant to address the typical River basins problems. The cases also revealed challenges for communities of practice approaches in several unique aspects, such as the limited participation of stakeholders, too much emphasis on formal projects' objectives rather than informal objectives and the more ad hoc jointly developed shared ways of solving problems.

The model cases highlight, in particular, the kind of social structure that promises to nurture robust mutual engagements between researchers/experts and policy-makers/stakeholders in the climate change adaptation arena. The communities of practice approach can allow participants to address the challenge of how science can interact with policy, by focusing on the locally developed shared ways of doing as social processes and practices – with regard to water resource vulnerability and adaptation in a climate change context. This allowed us to envision the science-policy interface as vigorous and dynamic communities of practice for successful relationships necessary to tackle relevant practical problems in the era of global change, where solutions (involving complex policy process and societal values) largely depend on the nature of the social arenas in which these problems are defined.

6.2 Policy Implications

This doctoral dissertation was specifically inspired by the increasing need for the development and application of innovative approaches to the holistic understanding of water resources' issues due to climatic shocks and consequent effects on related ecosystems. The present work constituted methodologies that were anchored in the regional risk assessment framework and applied relevant DSS tool and techniques to seek solutions to the most pressing policy related questions, such as what will be the magnitude of potential climate change impacts on regional groundwater resources? What consequences will climate related impacts on groundwater have on dependent ecosystems? How do present DSSs related methodologies and techniques support the assessment and management of climate change impacts? How does the spatial mapping of climate change induced consequences support regional adaptation planning for vital ecosystems? How can the social dynamics in regional climate change adaptation project be conceptualized in order to better influence the definition of robust adaptation policy? Accordingly, the dissertation developed and applied methodologies and concepts that include interdisciplinary perspectives and integrates different piece of work related to the analysis of DSSs related methodologies and approaches for the assessment and management of climate change issues, the evaluation of regional climate change impacts on coastal groundwater aquifer and the characterization of consequent risks for dependent ecosystems, and the development and application of new approach to the social context that exist within climate change adaptation arena.

Within this framework of analysis, the dissertation highlighted the relevance of developing climate change impact assessment and management at the regional scale (i.e. subnational and local scale), according to the requirements of policy and regulatory frameworks and to the methodological and technical features of relevant DSSs. For example, the several examined DSSs provide functionalities useful to support the assessment phases of regulatory frameworks, through integrated regional risk assessment approach that is also an ecosystem approach to the characterization and ranking of regional risks due to climate change and anthropogenic pressures. This will support the understanding of the dynamic and complex nature of coastal impacts and consequent risks on related ecosystems, through adequate identification and description of results from impacts and risks analysis.

The presented spatially resolved methodology provides an integrated means to identify key aspects of coastal groundwater and surface water system interactions and together understand the spatial vulnerability of the regional coastal aquifer and its dependent ecosystems to potential seasonal changes in climate variables and anthropic pressures. In this way, the dissertation further underscores the need for investigating and monitoring coastal groundwater resources, to provide valid knowledge of environmental features and conditions needed to understand the dynamics of groundwater systems and to analyse effectively their complex issues, considering both short and long timeframe scenarios within an ecosystem approach. This would further reduce the level of uncertainty that often plagues climate change impact assessments and thus provide relevant information most needed for managers and planners' adaptation practices. The implementation of the spatially resolved methodology with the GIS-based DESYCO tool 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 coastal 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 within the region. On the whole, the results support the sustainable management of coastal groundwater resources and its dependent ecosystems in the lower Esino River valley, by the means of relevant indications useful to adapt current regional water managers' planning and management strategies to future climate changes, in accordance to key principles of the WFD and Groundwater Directive.

Finally, the dissertation enhances the understanding of the social context in climate change adaptation arena and how this context potentially promotes and sustains mutual engagement and the negotiation crucial for the inclusion of scientific knowledge into adaptation policies, and for joint problem solving that engages researchers/experts and (climate) policy-makers/stakeholders. The social context facilitates continuous interactions and a relationship that is premised on participation, commitment and trust, and therefore influences policy-making, as is the scientific knowledge.

Accordingly, the dissertation draw on the significance of the social dynamics in the science-policy interface and how these could nurture and promote formal and informal relations needed to negotiate different expertise and narrow apparent boundaries. In particular, when the interface is focus on the locally developed shared-ways of doing as social processes and practices, which can stimulate experience and competence necessary to tackle relevant practical problems in the era of global change. Where solutions that involve complex policy process and societal values depend largely on the nature of the social context in which these problems are often defined.

6.3 RECOMMENDATIONS AND FUTURE CONSIDERATIONS

According to the analyses presented herein, this dissertation demonstrates that effective investigation and protection of coastal aquifers should be based on an ecosystem approach, which is focused on different future climate change hazard scenarios according to both short and long timeframes to further reduce the level of uncertainty that often plagues the climate change impacts assessment. This work also highlights the need to improve the understanding of coastal systems and how this relates to the complexity of coastal environments, because the sustainable planning and management of coastal systems requires not only an understanding of ecological features, but also demands the understanding of related socioeconomic conditions. Thus, coastal systems and related ecosystems studies at the local or regional scale should be properly carried out to enhance the evaluation of effects and the identification of areas in need of urgent adaptation measures. In addition, the dissertation establishes that the social structure in climate change adaptation projects potentially promotes and sustains mutual engagement and the negotiations crucial for the inclusion of scientific knowledge in the definition of practical climate change adaptation strategies.

However, the dissertation also uncovers significant areas that demand further attention. The spatially resolved methodology applied with the GIS-based DESYCO tool provides an effective model for effective analyses and processing of large heterogeneous quantities of spatial environmental data. Thus, we can improve the flexibility and adaptability of this methodology in terms of spatial and temporal scales. Still, there is a need to improve the definition and normalization of hazard and vulnerability factors, especially susceptibility and value factors that require in-depth understanding and insights from both scientists and local stakeholders/managers to further improve the methodological output that could be influenced by uncertainty in this normalization process. Further studies should consider approaches to understand the casual link between identified stressors (i.e., climate change) and groundwater-dependent ecosystems, through a defined pathway (i.e., groundwater systems). This will contribute to the effective protection and management of groundwater-dependent ecosystems, even though groundwater residence, hydrogeological and climatic conditions vary in spatiotemporal scales. While the results presented suggest the relevance of coastal aquifer qualitative conditions, high attention will likely be needed for groundwater quantitative status to adequately support groundwater-dependent ecosystems planning and management. Finally, it will be worthwhile to apply communities of practice concepts as an analytical framework for regional climate change adaptation in order to verify its efficacy and potentials for practical climate change adaptation policies.

APPENDIX A

Figure1. The case study area

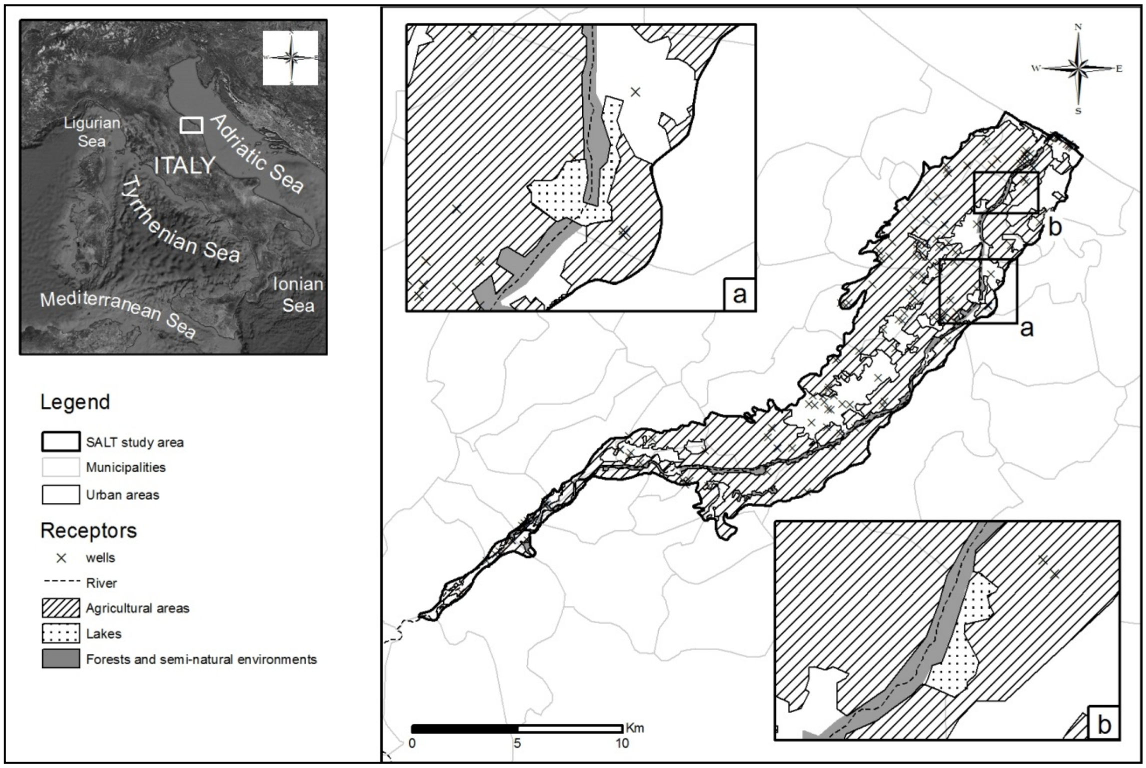


Figure 2. RRA conceptual framework for the analysis of climate change impacts on coastal zone at the regional scale

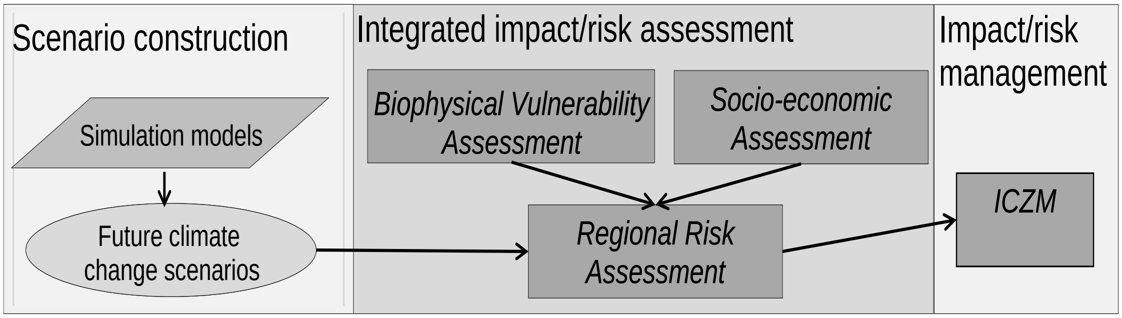


Figure 3. The model chain defines within the SALT project. SST: Sea Surface Temperature; T: Temperature; S: Salinty; u: zonal velocity; v: meridional velocity)

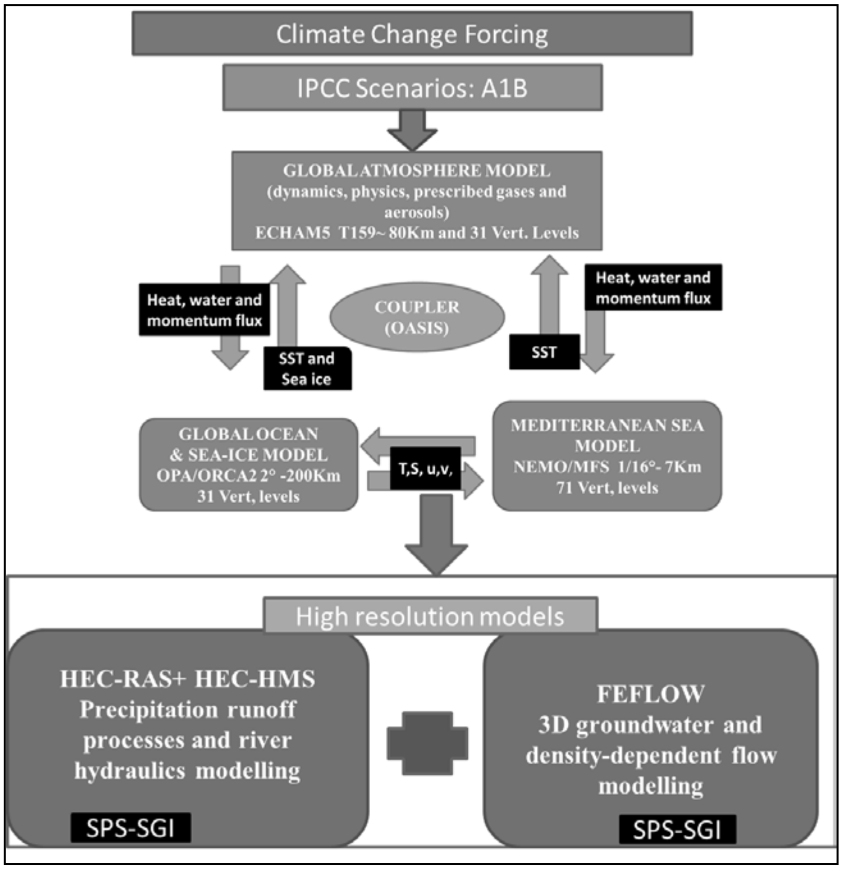


Figure 4. Exposure map for the Groundwater Level Variation impact, summer season

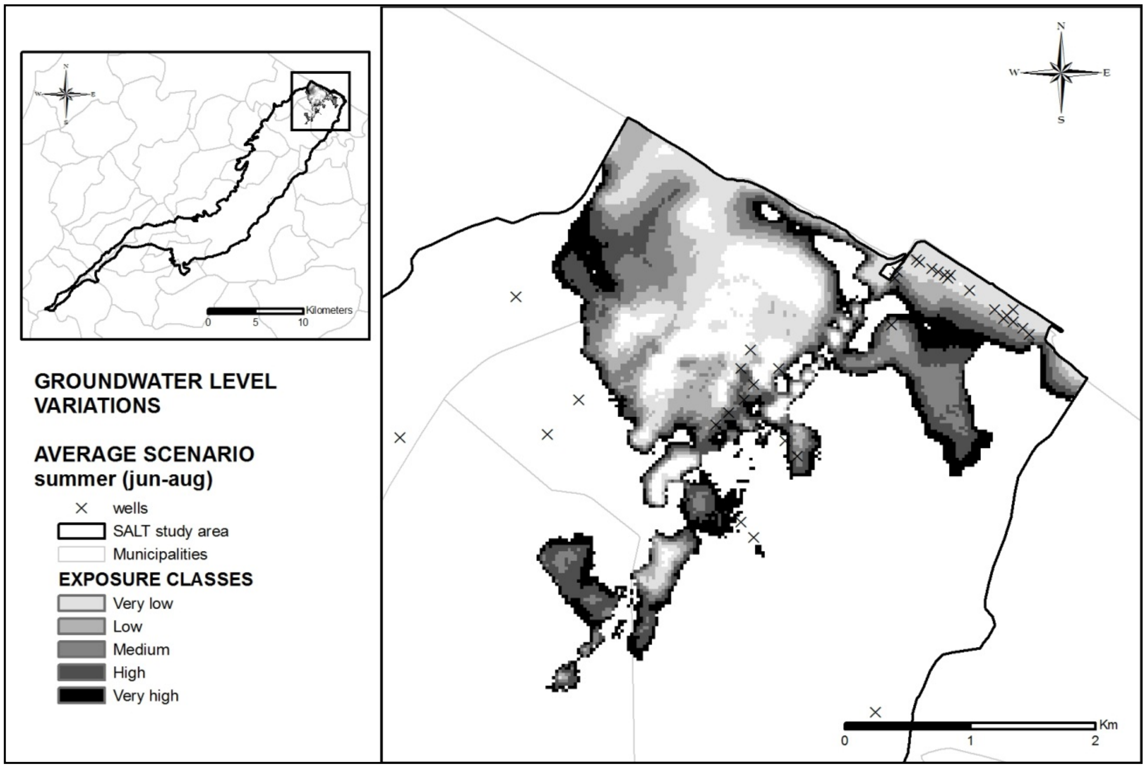
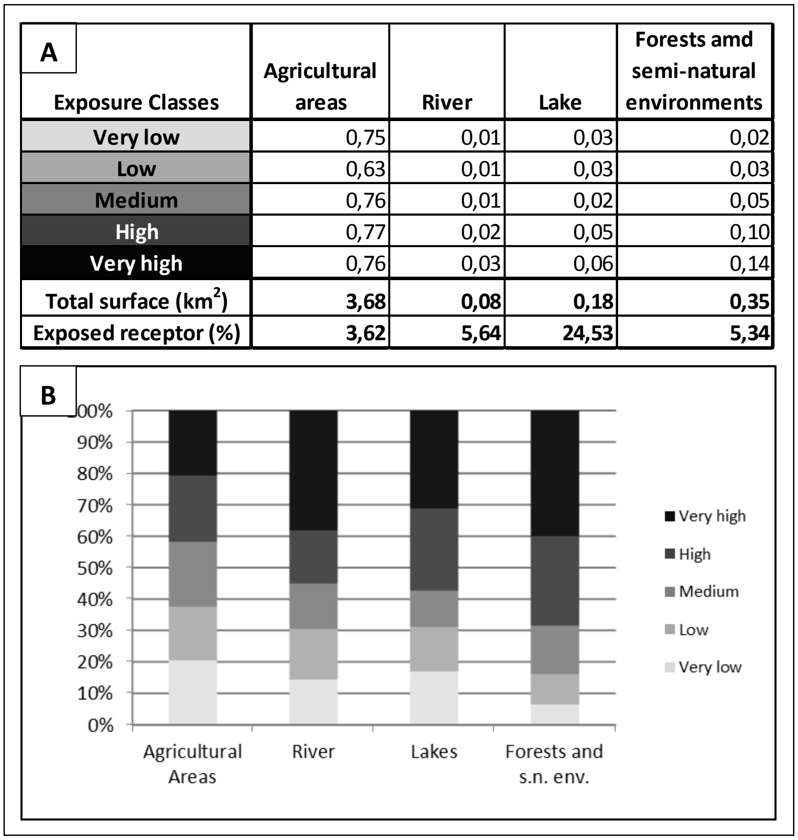


Figure 5. A) Distribution of the territorial surface (Km^2) associated with each exposure class for the Groundwater Level Variation impact, average scenario, summer season. B) Distributions of the percentage of exposed surface associated with each exposure class



A

Exposure Classes	Agricultural areas	River	Lake	Forests amd semi-natural environments
Very low	0,75	0,01	0,03	0,02
Low	0,63	0,01	0,03	0,03
Medium	0,76	0,01	0,02	0,05
High	0,77	0,02	0,05	0,10
Very high	0,76	0,03	0,06	0,14
Total surface (km^2)	**3,68**	**0,08**	**0,18**	**0,35**
Exposed receptor (%)	**3,62**	**5,64**	**24,53**	**5,34**

Figure 6. Exposure map for the Saltwater Intrusion impact, winter season

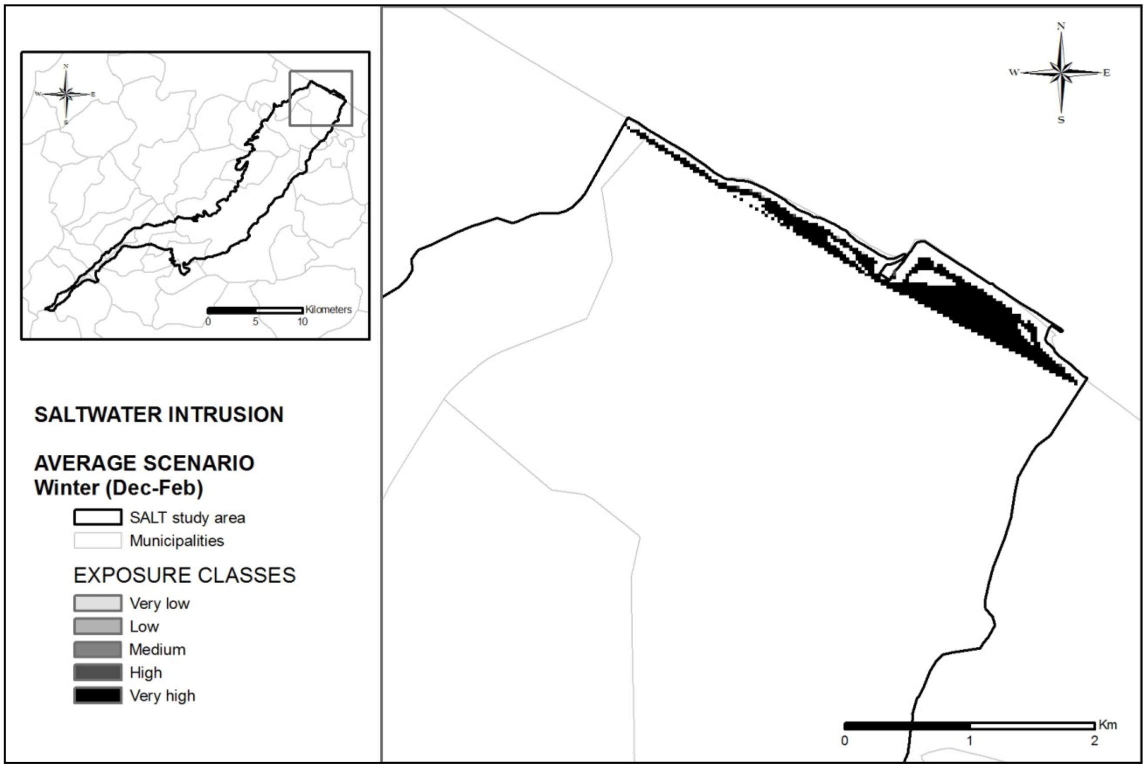


Figure 7. Susceptibility map for the Groundwater Level Variation impact

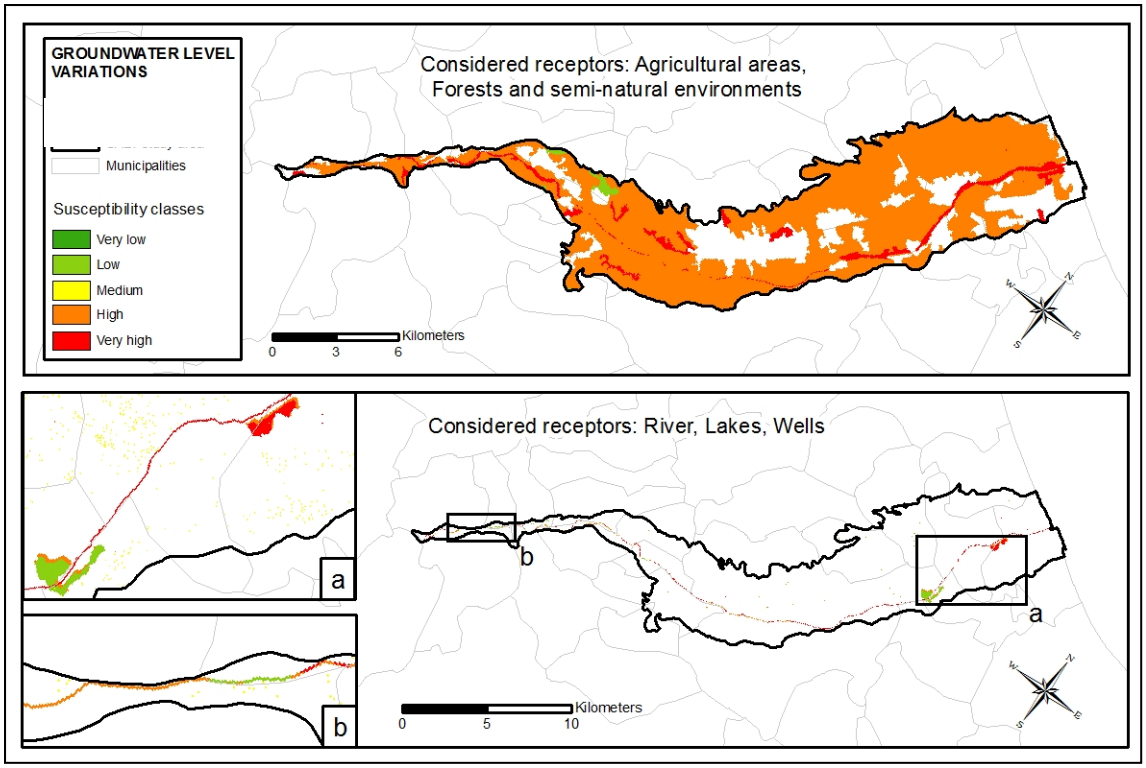


Figure 8. Susceptibility map for the Saltwater Intrusion impact

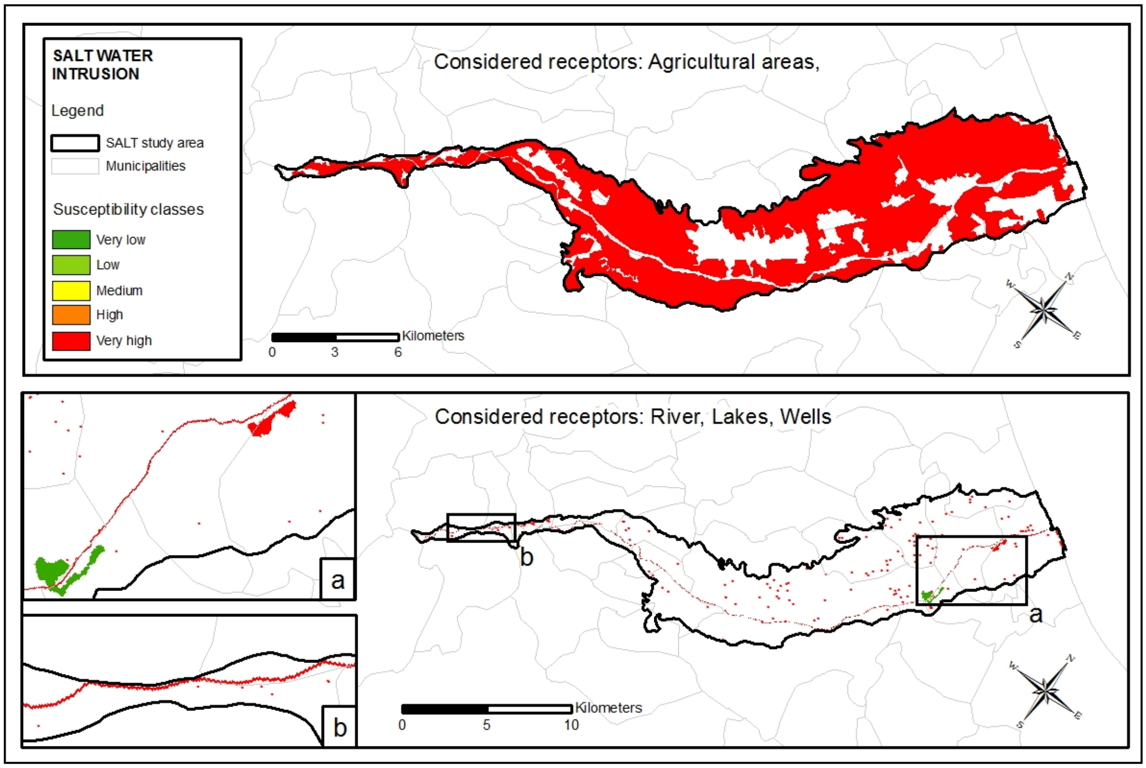


Figure 9. Risk map for the Groundwater Level Variation impact, summer season

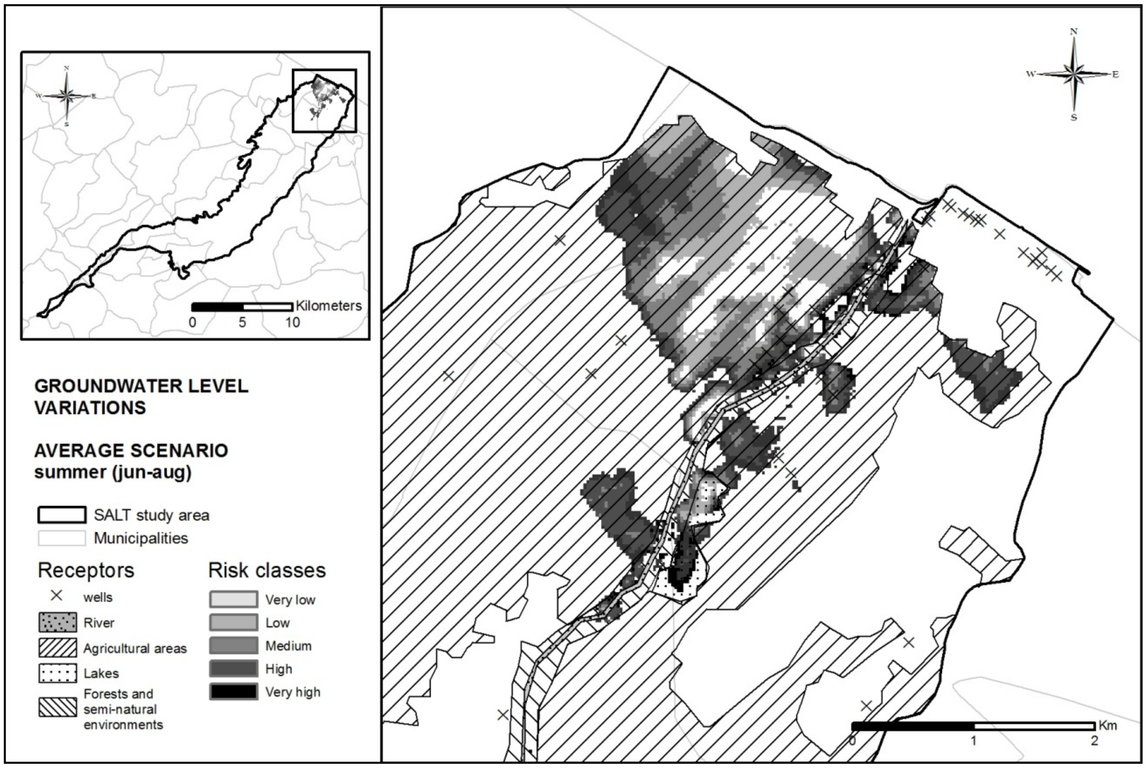


Figure 9. A) Distribution of the territorial surface (Km^2) associated with each relative risk class for the Groundwater Level Variation impact, average scenario, summer season. B) Distribution of the percentage of exposed surface associated with each relative risk class

A

Risk Classes	Agricultural areas	River	Lake	Forests amd semi-natural environments
Very low	0,99	0,01	0,03	0,03
Low	0,93	0,01	0,03	0,05
Medium	1,07	0,01	0,02	0,10
High	0,62	0,01	0,05	0,13
Very high	0,07	0,03	0,04	0,05
Total surface (km^2)	**3,68**	**0,07**	**0,18**	**0,35**
Exposed receptor (%)	**3,62**	**5,21**	**24,44**	**5,33**

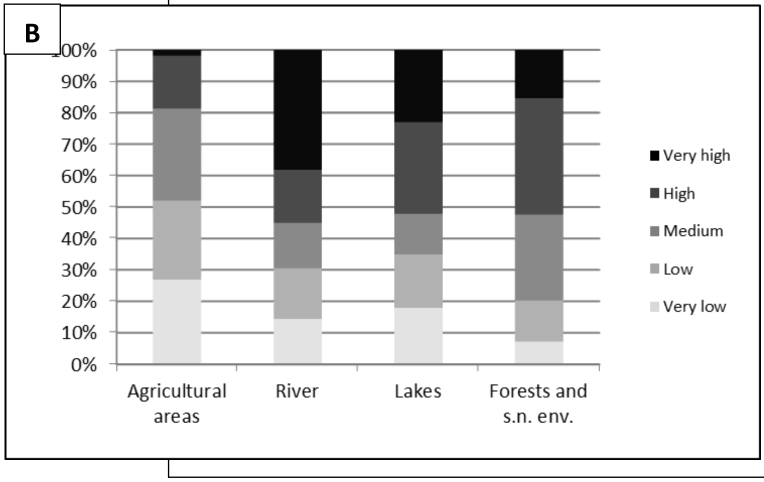


Figure 10. Value map for the Groundwater Level Variation impact

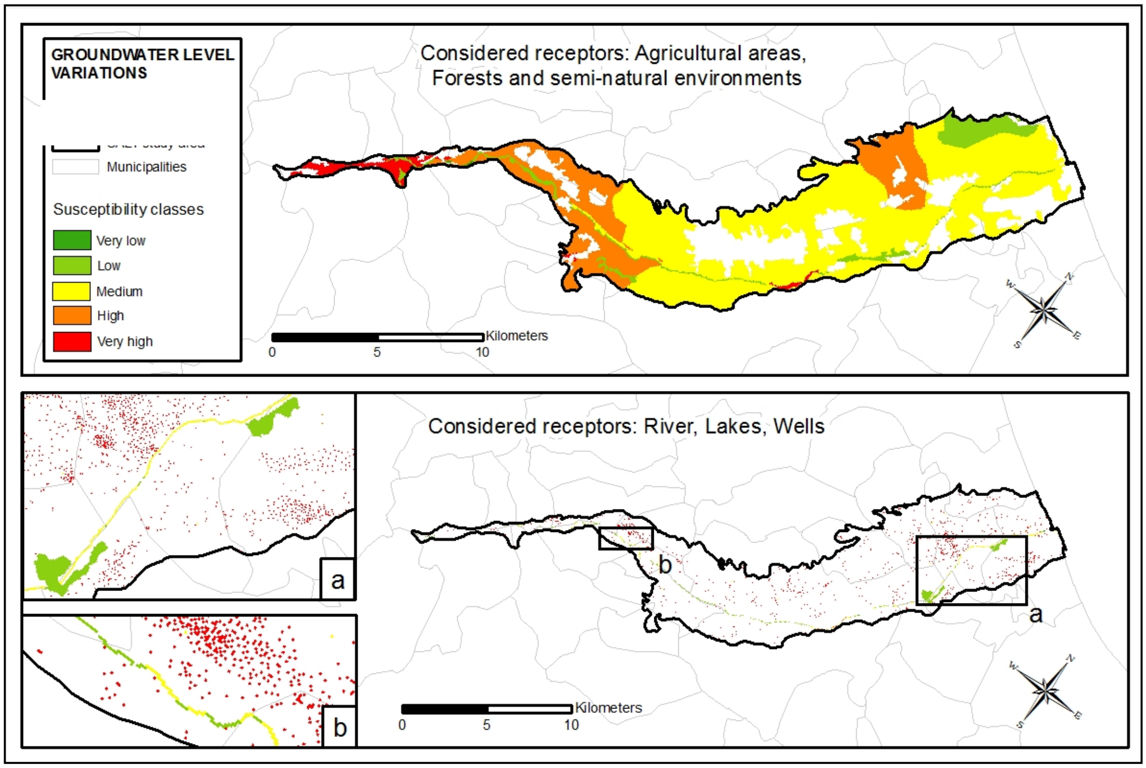


Figure 11. Damage map for the Groundwater Level Variation impact, summer season

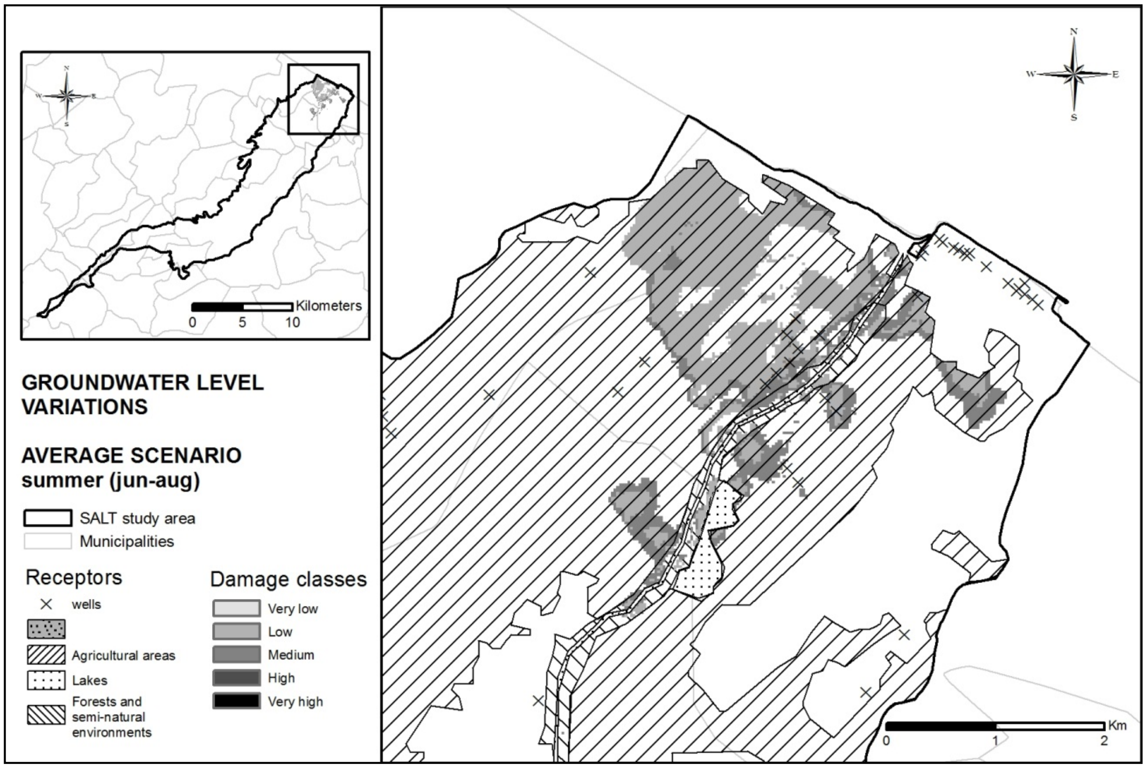


Table1. The vulnerability matrix for the lower Esino River valley

IMPACTS ON WATER QUALITY					
SALTWATER INTRUSION	Present depth to saline interface.	Present depth to saline interface.	Present depth to saline interface.	Present depth to saline interface.	
	Water salinity.	Basin level or extension.	Crop economic value.	Wells use typology (drinking, domestic, and irrigation, industrial).	
	River flow (average).	Protection level (e.g. WFD protected areas).			
	River bed slope.				
	Protection level (e.g. WFD protected areas).				
IMPACTS ON WATER QUANTITY					
GROUNDWATER LEVEL VARIATIONS	Present depth to groundwater.	Present depth to groundwater.	Present depth to groundwater.	Present depth to groundwater.	Present depth to groundwater.
	River flow.	Basin level or extension.	Crop typology (water requirements).	Average flow / volume pumped.	Extension of forests.
	Protection level (e.g. WFD protected areas).	Protection level (e.g. WFD protected areas).	Crop economic value.	Wells use typology (drinking, domestic, irrigation, industrial).	Vegetation cover typology (water requirements).
					Extension of forests.
					Vegetation cover typology.
					Protection level (e.g. WFD protected areas).

Legend:	**Pathway factors**	**Susceptibility factors**	**Value factors**

Table 2. Hazard matrix for the lower Esino River valley

IMPACTS	HAZARD METRIC
IMPACTS ON WATER QUALITY	
SALTWATER INTRUSION	Depth of the saltwater interface
IMPACTS ON WATER QUANTITY	
GROUNDWATER LEVEL VARIATIONS	Groundwater mean level

Table 3. Description of the receptors considered within the lower Esino River valley

RECEPTORS	DESCRIPTION
River	Rivers are recurrent water bodies or streams which can be partially underground and flows mainly to the surface at a rate that varies with the seasons or climatic conditions. For this application we consider the Esino river as receptors because it directly lies above the aquifer and as such recharge the aquifer water level.
Lakes	Lake means a body of living stagnant water, mostly fresh water collected in a geomorphological depression. Lakes could be natural or artificial that can also be regarded as seasonal. For the SALT project, two lakes within the lower Esino river valley were identified and considered.
Agricultural areas	Agricultural areas are all portions of land within the case study area used for agricultural activities. This includes arable land for gardens and other perennial plants, meadows and natural pastures: arable land (lands under a rotation system used for annually harvested plants and, fallow lands which are permanently or not irrigated), pastures lands which are permanently used for fodder production (http://sia.eionet.europa.eu/CLC2000/classes).
Wells	Wells in general are man-made structure usually circular in shape and vary in size, through which freshwater is extracted from unconfined or confined groundwater aquifers. Dug, drilled and driven wells are used to pump water to the surface; instead artisan wells do not pump water because of the natural pressure that forces the water up from confined aquifers and out of the well (U.S. Geological Survey, 1982).
Forests and semi-natural environments	The extent of land cover including the forests (coniferous, mixed and broad-leaved), scrub and/or herbaceous vegetation (natural grasslands and transitional woodland shrub) and open spaces with little or no vegetation (sand dunes, beaches and sparsely vegetation) http://sia.eionet.europa.eu/CLC2000/classes.

Table 4. Definition of the vulnerability factors considered for the application of the RRA to the Esino River basin

FACTORS	DEFINITION
Pathway factors	
Present depth to saline interface.	Depth of saltwater interface, i.e. the distance of the considered receptor from the saltwater interface(m).
Present depth to groundwater.	The distance of water table from the ground surface (m), or of the well filter from the ground surface (m) for wells.
Susceptibility factors	
Water salinity	The degree of concentration of salts in water usually estimated by considering the components more abundant (CL^-, Na^+, Ca^{2-}, Mg^{2+}, $S04^{2-}$) in absolute value ppm, mg/l and psu.
Basin level or extension	The extension of the basin (sq km).
River flow (average)	The volume of water that moves over a designated point over a fixed period of time (m^3 /sec (EPA, 2011)
Vegetation cover typology (water requirement)	The typology of vegetation (e.g. annual and permanent crops, scrub and herbaceous vegetation).
Crop typology (water requirement)	The typology of crops (e.g. annual crops, arative, perennial crops).
Average flow / pumped volume	The total volume of water extracted from wells per year.
Extension of forests	The extension of forests and semi-natural environments (sq km) within the regional landscape.
Value factors	
Crop economic value	Presence of crops in defined geographic areas which produce value products for European area (e.g. DOC and DOCG wine from vineyards).
Protection level	Degree of protection associated with the area in which the receptor is located and dependent on the presence of natural areas or protected sites for biodiversity conservation established under current legislation (e.g. L.349/1991 on protected areas at the national level, or Natura 2000 sites at the European level).
Vegetation cover typology (water requirement)	The typology of vegetation that cover an area (e.g. poor vegetation and meadow, vegetation with shrubbery, wood).
Extension of forests	The extension of forests and semi-natural environments (sq km) within the regional landscape.

Table 5. Description of data sources for the ESINO River basin

RECEPTORS	DATA TYPOLOGY	FORMAT	SCALE	SOURCE
RIVER	Hydrography of Esino river	Shapefiles	Regional	Regione Marche
LAKES	Lakes shapes from Corine Land Cover 2006	Shapefiles	Supra-national	www.eea.europa.eu/data
AGRICULTURAL AREAS	Agricultural areas shapes from Corine Land Cover 2006	Shapefiles	Supra-national	www.eea.europa.eu/data
FORESTS AND SEMI-NATURAL ENVIRONMENTS	Forests, scrubs and/or Herbaceous vegetation associations shapes from Corine Land Cover 2006	Shapefiles	Supra-national	www.eea.europa.eu/data
WELLS	Wells localization in the study domain	Shapefiles	Regional	Provincia di Ancona, Multiservizi Spa, SGI – Studio Galli Ingegneria Spa, SPS – Società Progettazione Servizi Srl
VULNERABILITY FACTORS	**DATA TYPOLOGY**	**FORMAT**	**SCALE**	**SOURCE**
GROUNDWATER MEAN LEVEL (PRESENT)	Estimates of average groundwater level (from hydro-geological modeling) at present time	Shape file	Local	SGI – Studio Galli Ingegneria Spa
RIVER FLOW (AVERAGE)	Annual mean flow rate for Esino river	Shapefiles, Excel files	Local	Regione Marche - Protezione Civile
BASIN LEVEL / EXTENSION	Lakes extensions (sq. km) derived from Corine Land Cover 2006	Shape files	Supra-national	www.eea.europa.eu/data
CROP TYPOLOGY (WATER REQUIREMENTS)	Literature data for Corine Land Cover 2006 (crop typologies classification)	Shapefiles	Supra-national	www.eea.europa.eu/data, Literature data
VEGETATION COVER TYPOLOGY (WATER REQUIREMENTS)	Literature data for Corine Land Cover 2006 (vegetation typologies classification)	Shapefiles	Supra-national	www.eea.europa.eu/data, Literature data
CROPS ECONOMIC VALUE	Economic value for crop and other products (current data for protected products accordingly to national and regional regulations)	Shapefiles	Regional	Regione Marche - Servizio Agricoltura, Forestazione e Pesca
DEPTH OF WELL FILTER (WELLS)	Technical data regarding filter localization on wells	Shapefiles, Excel files	Local	Provincia di Ancona, Multiservizi Spa, SGI – Studio Galli Ingegneria Spa
AVERAGE FLOW/VOLUME PUMPED (WELLS)	Technical data regarding utilization of wells	Shapefiles, Excel files	Local	Provincia di Ancona, Multiservizi Spa, SGI – Studio Galli Ingegneria Spa
WELLS USE TYPOLOGY (DRINKING, IRRIGATION, INDUSTRIAL)	Technical data regarding utilization of wells	Shapefiles, Excel files	Local	Provincia di Ancona, Multiservizi Spa, SGI – Studio Galli Ingegneria Spa
EXTENSION OF FORESTS	Forests and semi-natural environments extension (sq. km) derived from Corine Land Cover 2006	Shapefiles	Supra_national	www.eea.europa.eu/data
PROTECTION LEVEL (e.g.WFD PROTECTED AREAS)	Protected areas accordingly with national and international regulations (e.g. Natura2000 networks)	Shapefiles	Supranational / Regional	Regione Marche
ELEVATION FROM THE SALTWATER INTERFACE	DEM; estimates of average saltwater interface level (from hydro-geological modeling)	Shapefiles	Regional	SGI – Studio Galli Ingegneria Spa
WATER SALINITY (ESINO)	Water quality data for Esino river	Shapefiles, Excel files	Local	Regione Marche - ARPAM
RIVER BED SLOPE	Esino hydro-morphological characterization (from hydrological modeling)	HEC-RAS files	Local	SGI – Studio Galli Ingegneria Spa

Table 6. Classes and scores defined for the susceptibility and value factors

Susceptibility factor	Class	Score	
		SI	GLV
Vegetation cover typology (water requirement)	Open space with little vegetation	-	0.3
	Scrub/herbaceous vegetation	-	0.7
	Land principally occupied by agriculture and natural vegetation	-	1
Crops typology (water requirement)	Vineyard/Olive	-	0.3
	Permanent crops	-	0.7
	Annual/pasture/arable crops	-	1
Extension of forests (sq.km)	37.5 – 86.4	-	1
	86.4 – 135.3	-	0.8
	135.3 - 184.2	-	0.6
	184.2 – 233.1	-	0.4
	233.1 – 282.0	-	0.2
Basin extension (sq.km)	26.0- 37.7	1	1
	37.7- 49.4	0.3	0.3
Water salinity (µS/cm, 20°C)	538 – 563	0.2	-
	563 – 588	0.4	-
	588 – 613	0.6	-
	612 – 637	0.8	-
	637 - 662	1	-
River flow (m3/s)	6,4 – 7,3	1	1
	7.3 – 8.2	0.8	0.8
	8.2 – 9.1	0.6	0.6
	9.1 – 10.0	0.4	0.4
	10.0 – 10.98	0.2	0.2
River bed slope (%)	-4.94 - -1.58	1	-
	-1.58 - 1.78	0.8	-
	1.78 - 5.14	0.6	-
	5.14 - 8.50	0.4	-
	8.50 - 11.87	0.2	-

Susceptibility factor	Class	Score	
		SI	GLV
Average volume yearly extracted from well (m^3)	1 -715582	-	0.2
	71558 - 143116	-	0.4
	1431164 - 214674	-	0.6
	214675 - 286233	-	0.8
	286233 - 357791	-	1

Value factor	Class	Score	
		SI	GLV
Protection level	SPAs, SACs	1	1
	Parks and reservoirs	0.6	0.6
	Absence	0.2	0.2
Crop economic value	11 DOC/DOCG products	0.2	0.2
	12 DOC/DOCG products	0.4	0.4
	13 DOC/DOCG products	0.6	0.6
	14 DOC/DOCG products	0.8	0.8
	15 DOC/DOCG products	1	1
Extension of forest (sq.km)	37.5 – 86.4	0.2	0.2
	86.4 – 135.3	0.4	0.4
	135.3 - 184.2	0.6	0.6
	184.2 – 233.1	0.8	0.8
	233.1 – 282.0	1	1
Vegetation cover typology	Open space/little or no vegetation	0.3	0.3
	Scrub/herbaceous vegetation	0.7	0.7
	Forests	1	1
Well use typology	Agriculture - Irrigation - Other	0.5	0.5
	Industrial	0.7	0.7
	Domestic - Drinking	1	1
	Unknown	1	1

Table 7. Exposure equation for the SI and GLV impacts

	Equation	Legend
IMPACTS ON WATER QUALITY		
EQUATION 1: GROUNDWATER LEVEL VARIATIONS	$E_{glv,s}\begin{cases} 0 & pf_1 > s_1 \\ \min\left(\frac{pf_1 + h_{glv,s}}{s_1}, 1\right) & otherwise \end{cases}$	$h_{glv,s}$= Amount of positive difference between present depth of groundwater and forecasted depth in scenario s (positive number). pf_1= Distance of groundwater from the ground level at present (positive number). s1= Distance of groundwater from the ground level which imply an effect of groundwater level decrease on receptors.
IMPACTS ON WATER QUANTITY		
EQUATION 2: SALTWATER INTRUSION	$E_{si,s}\begin{cases} 0 & h_{si,s} = 0 \\ \max\left(1 - \frac{pf_2 - h_{si,s}}{s_2}, 0\right) & otherwise \end{cases}$	$h_{si,s}$ = Amount of positive difference between depth of saltwater and forecasted depth in scenario s (positive number). pf_2= Present depth of saltwater from the ground level (positive number). s_2= Distance of saltwater from the ground level which imply an effect of saltwater level increase on receptors.

APPENDIX B

Figure A1.1. GLV Exposure maps for the lower Esino River valley (average scenario, summer season).

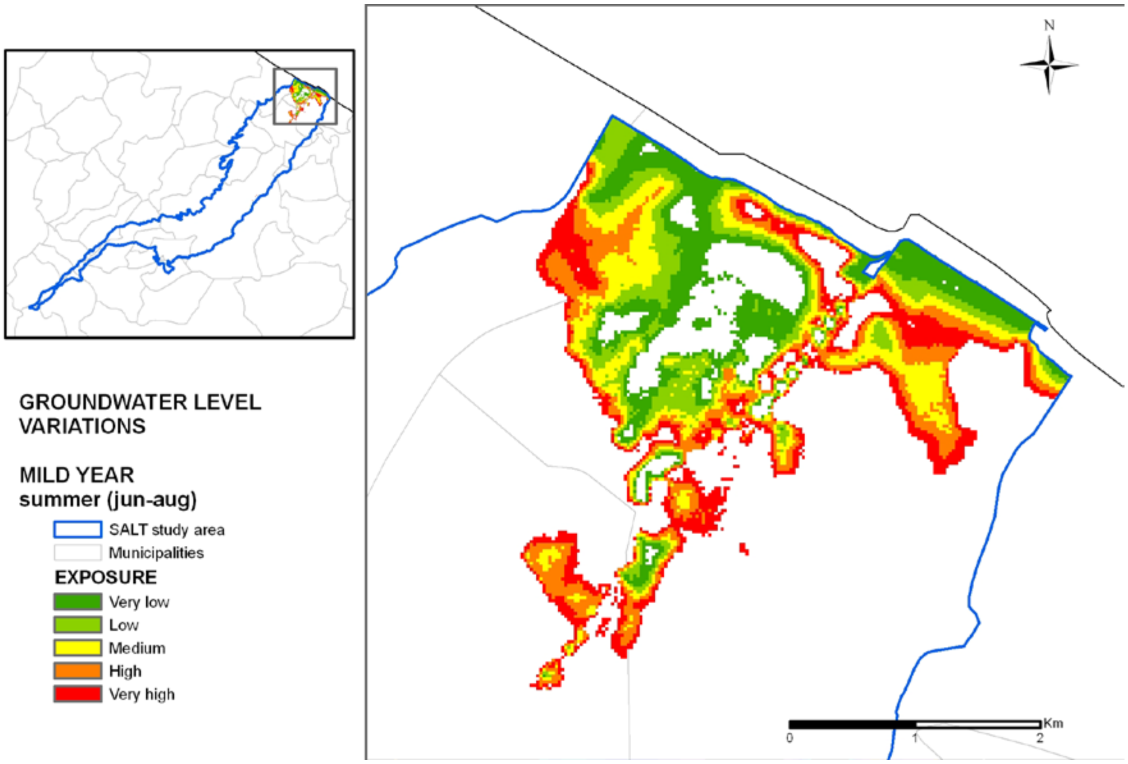


Figure A1.2. GLV Exposure maps for the lower Esino River valley (average scenario, summer season).

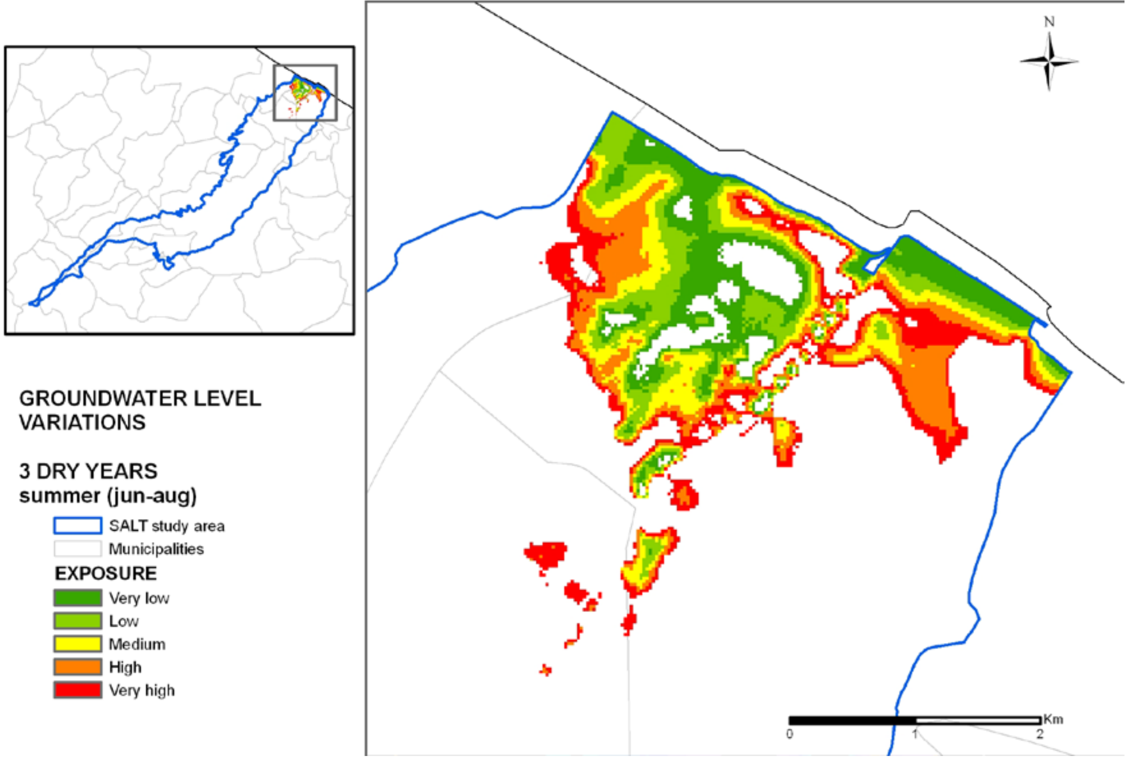


Figure A1.3. SI exposure maps for the lower Esino River valley (average scenario, winter season)

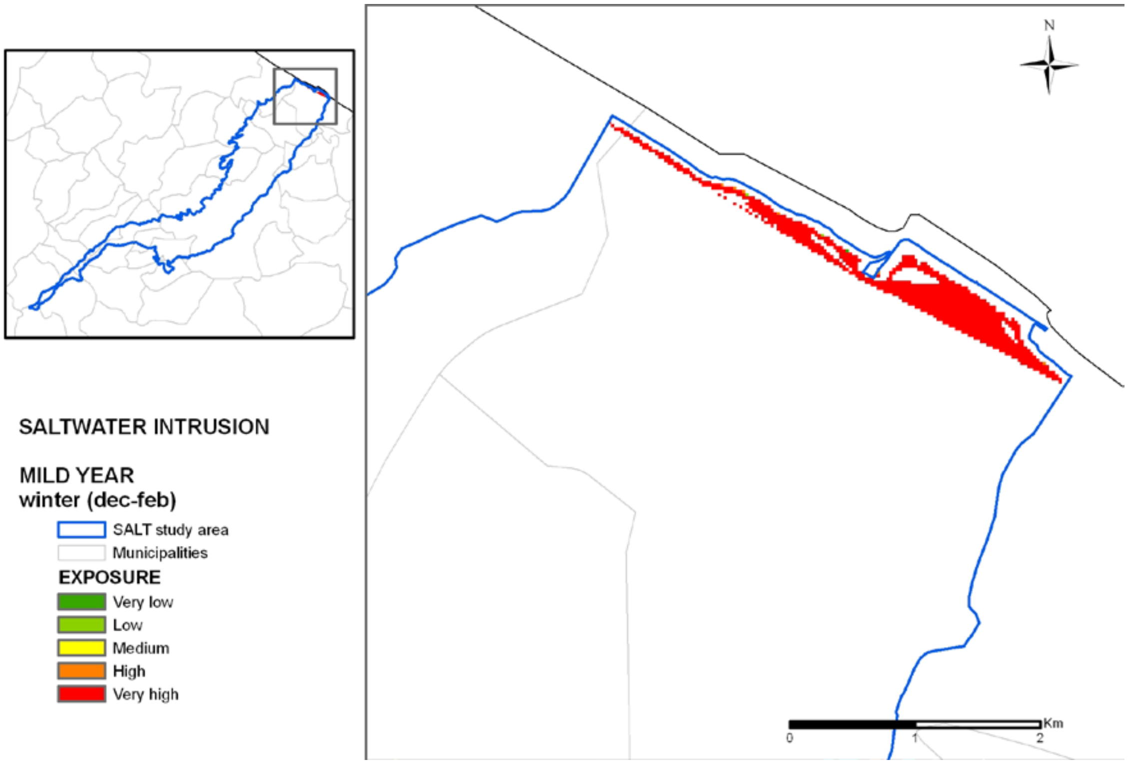


Figure A1.4. SI exposure maps for the lower Esino River valley (average scenario, summer season)

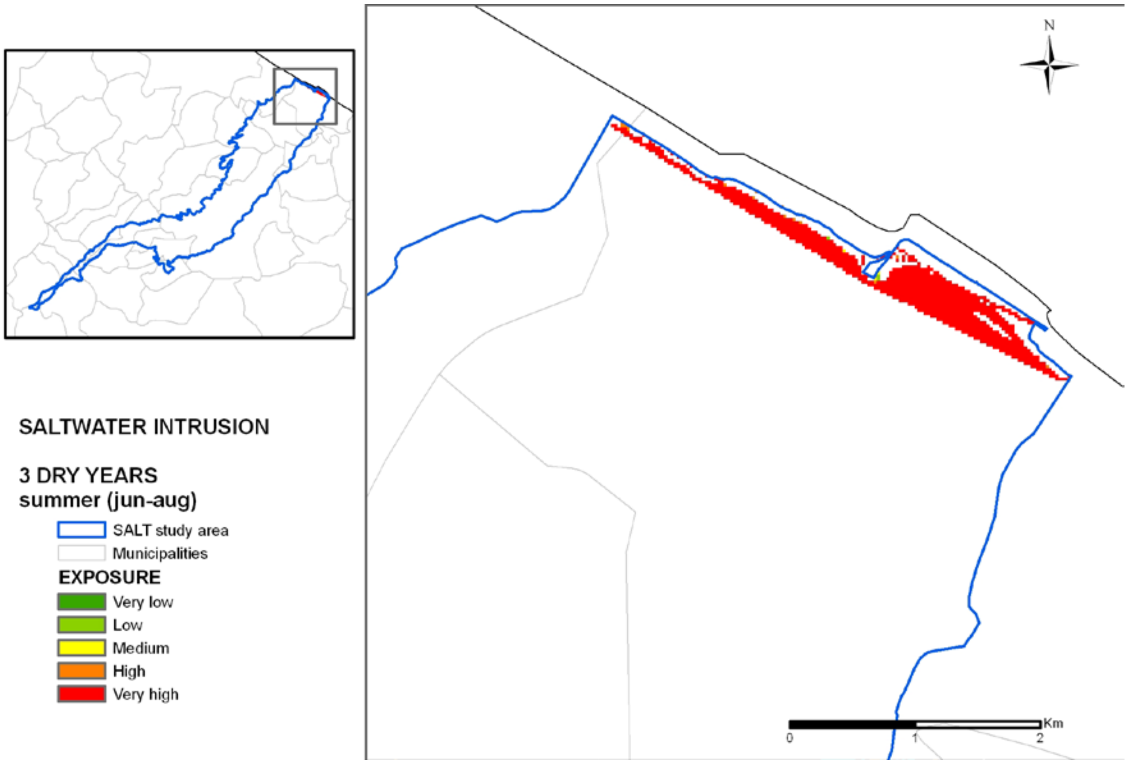


Figure A1.5. Risk map from GLV impact in the mild scenario for agricultural areas (summer season).

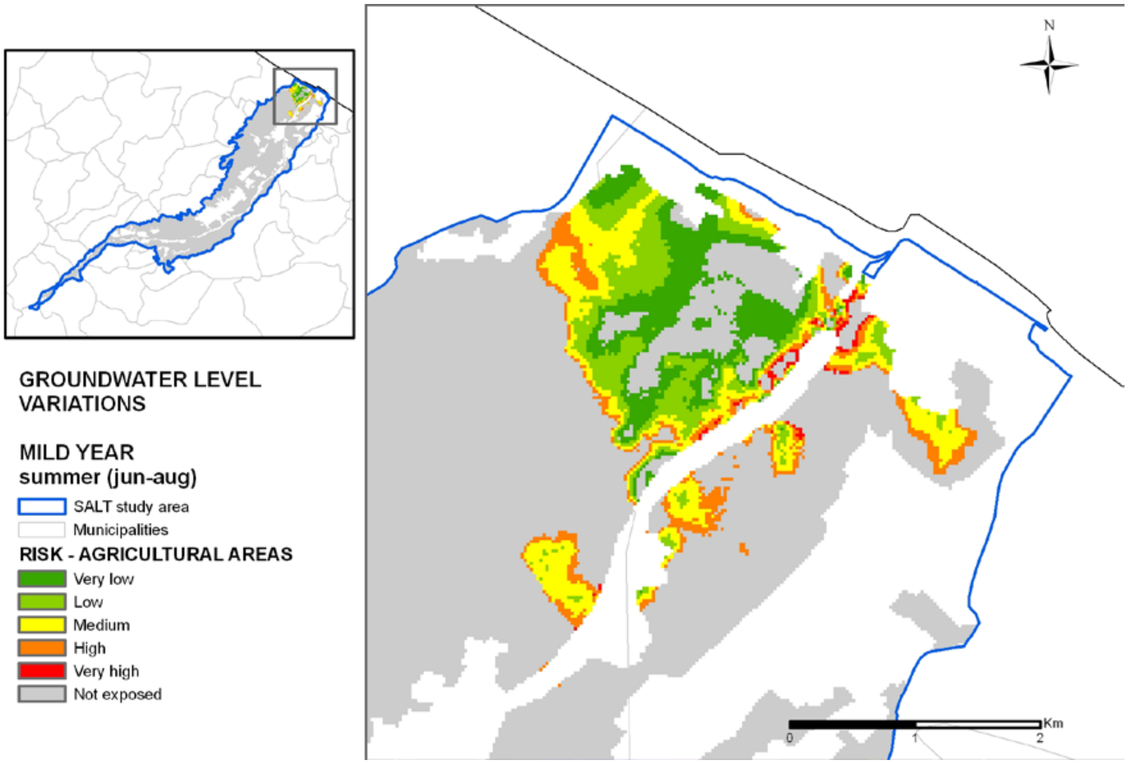


Figure A1.6. Risk map from GLV impact in the average scenario for Esino River (summer season)

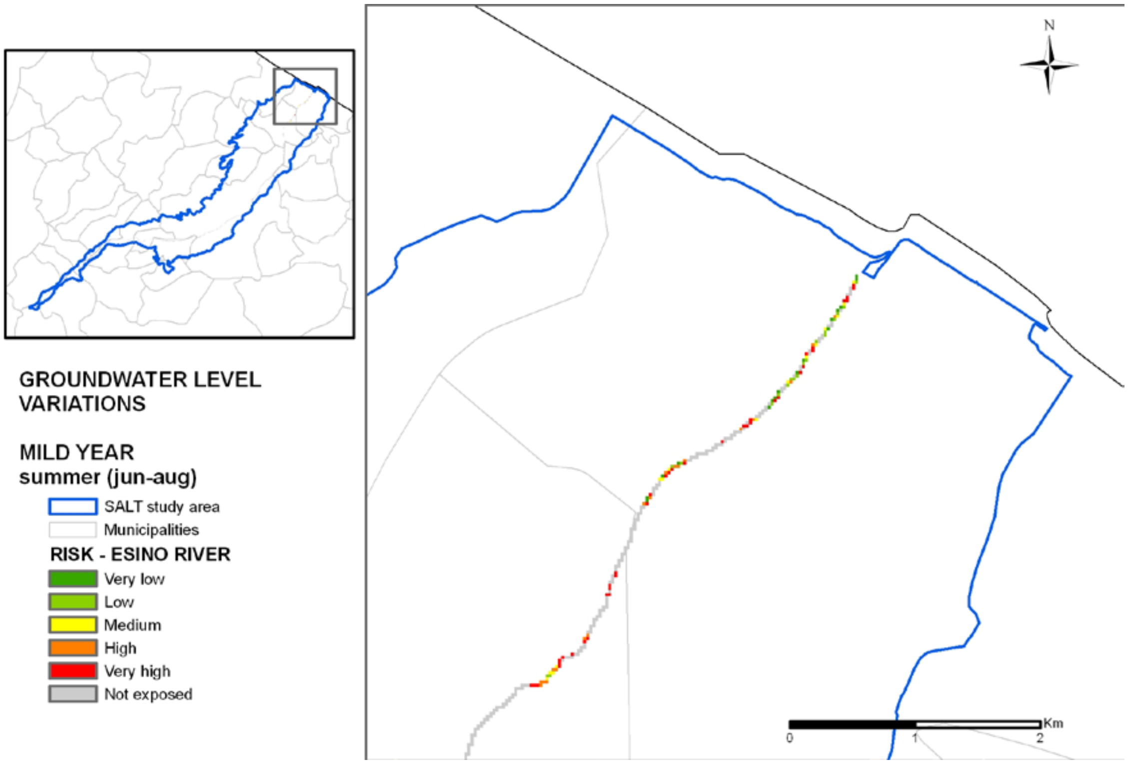


Figure A1.7. Risk map from GLV impact in the average scenario for lakes (summer season)

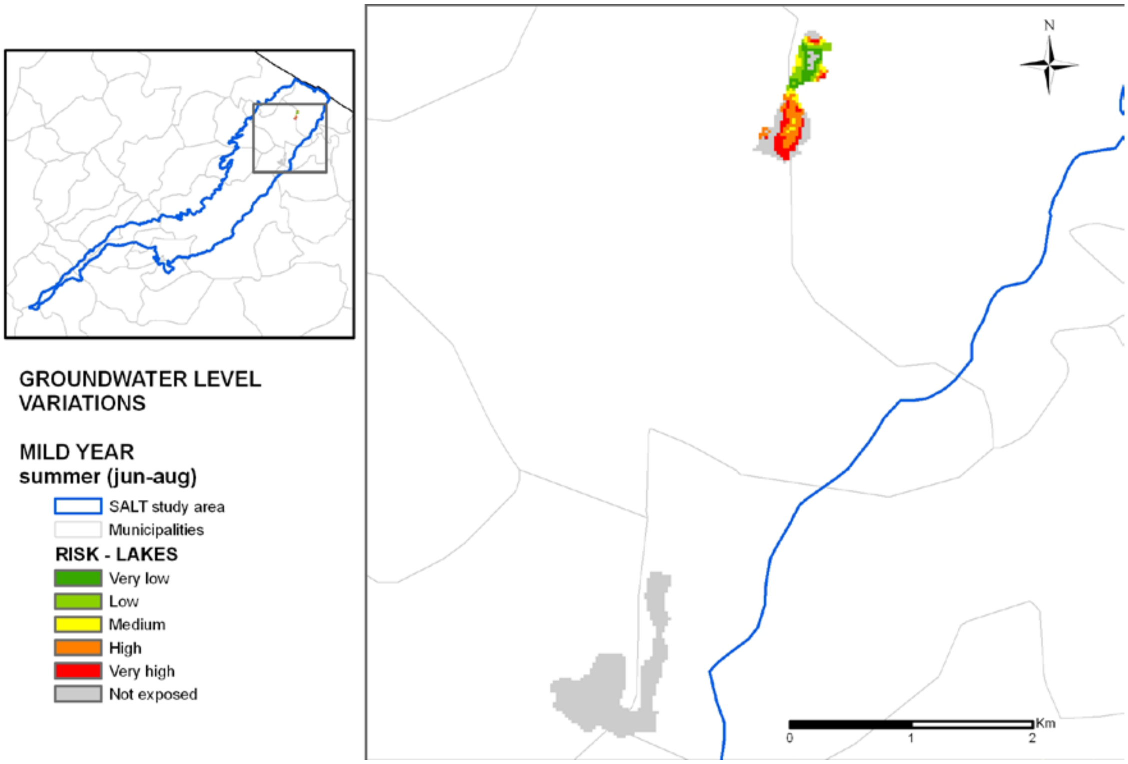


Figure A1.8. Risk map from GLV impact in the average scenario for forests and semi-natural environments (summer season)

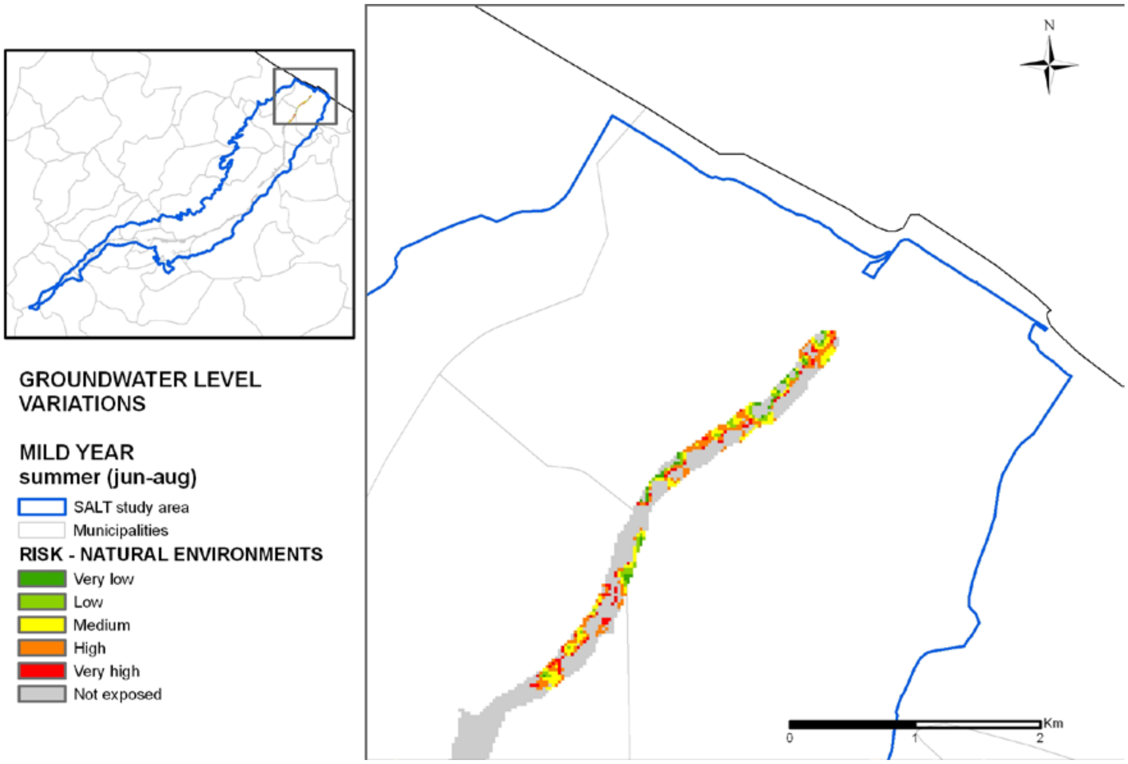


Figure A1.9. Risk map from GLV impact in the average scenario for agricultural areas (summer season)

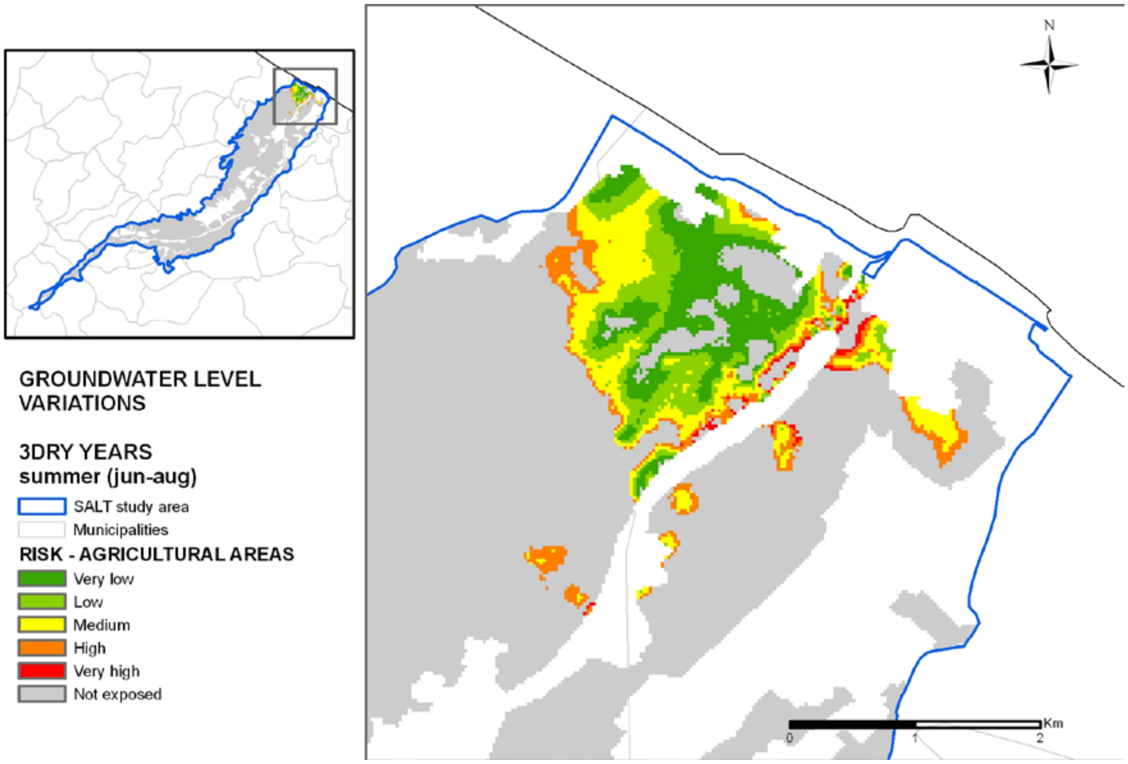


Figure A1.10. Risk map from GLV impact in the average scenario for Esino River (summer season)

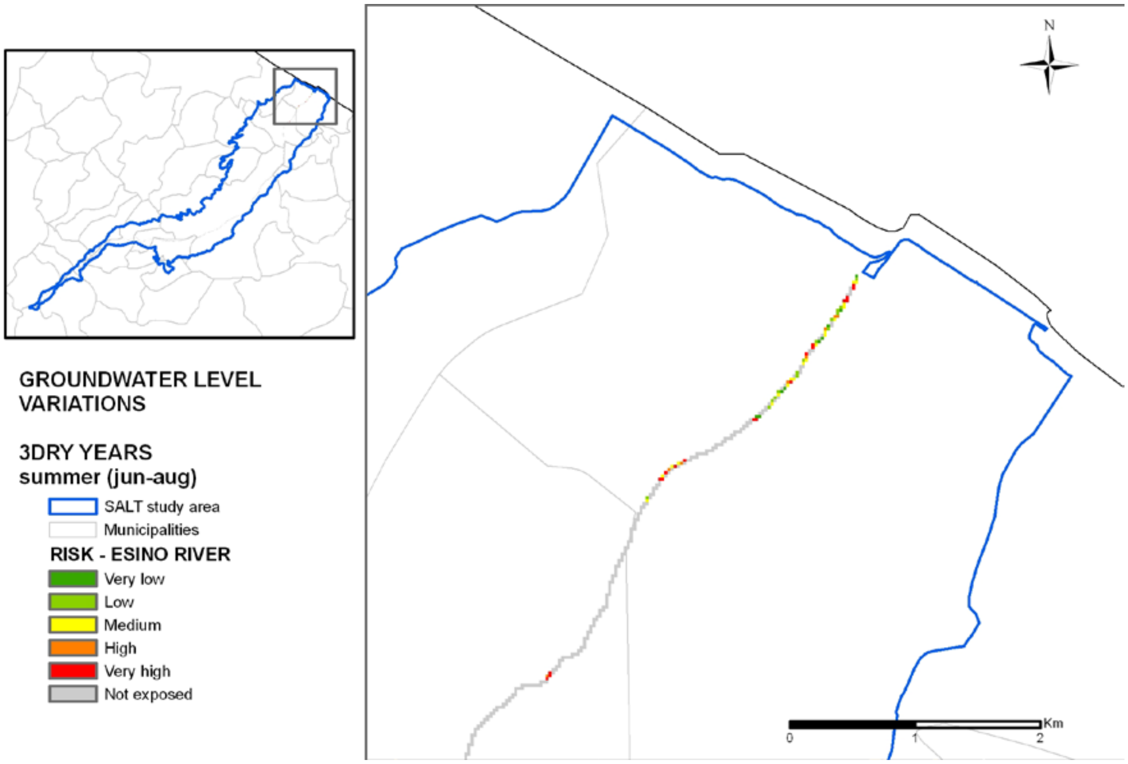


Figure A1.11. Risk map from GLV impact in the average scenario for lakes (summer season)

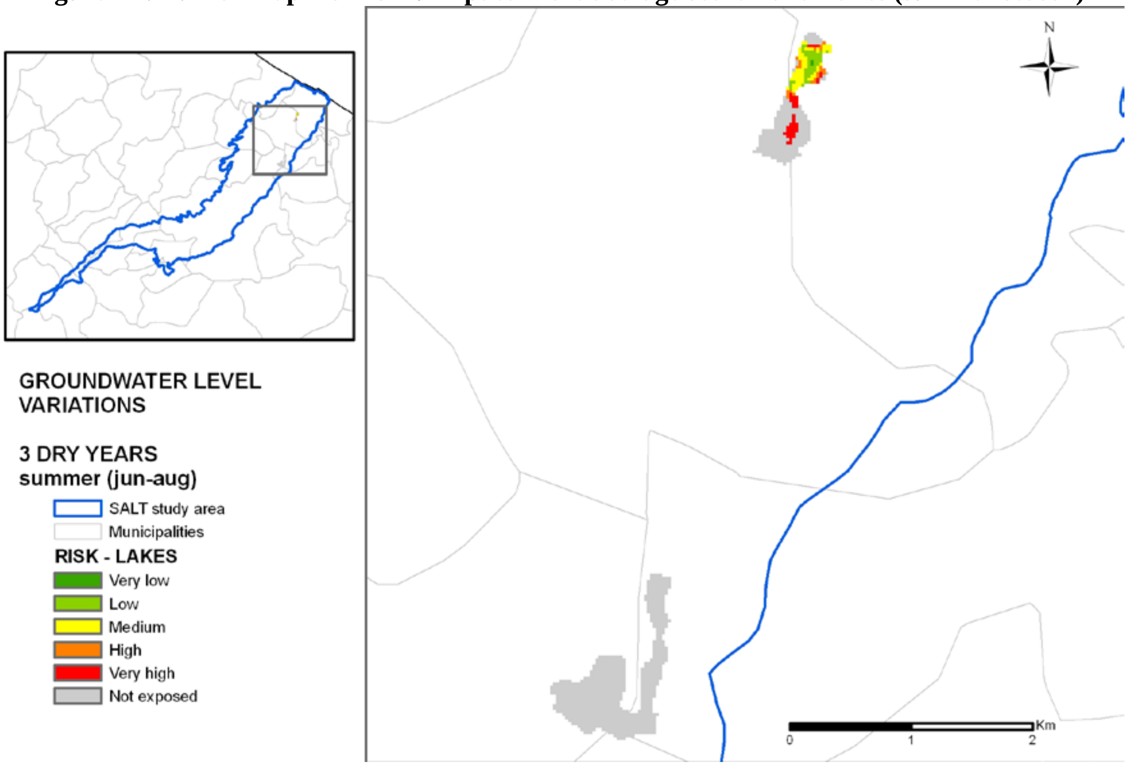


Figure A1.12. Risk map from GLV impact in the average scenario for forests and semi-natural environments (summer season)

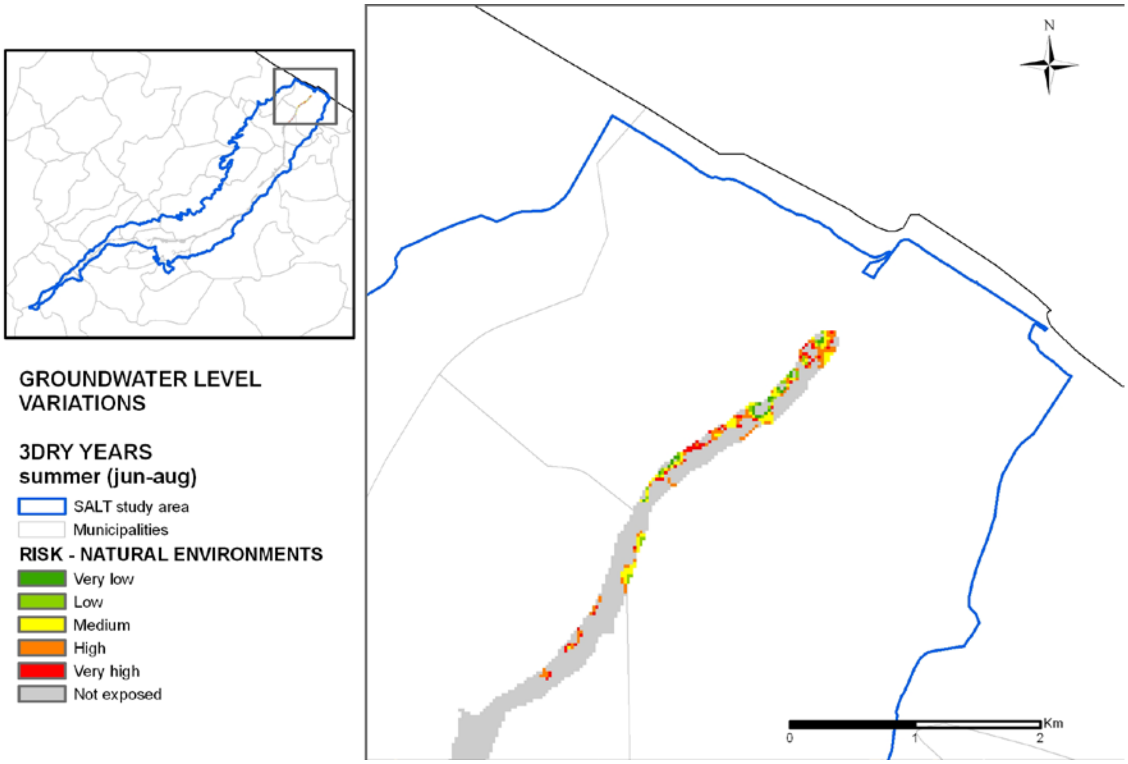


Figure A1.13. Damage map from GLV impact in the average scenario for agricultural areas (summer season)

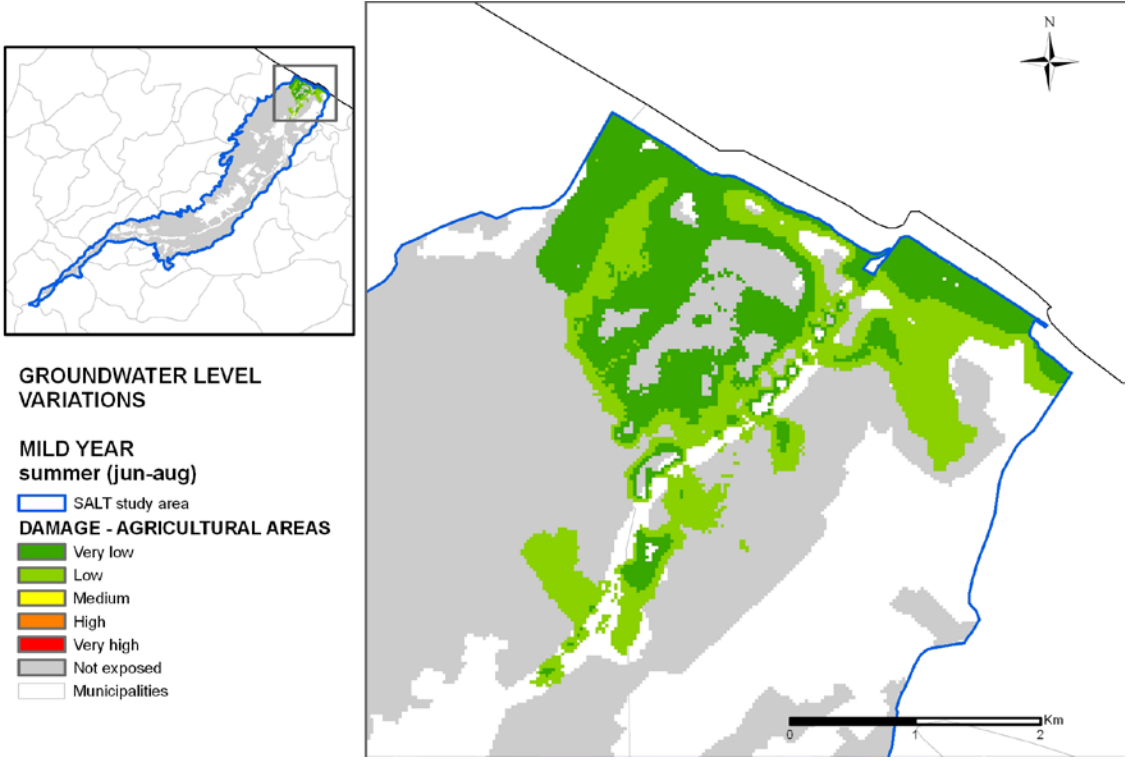


Figure A1.14. Damage map from GLV impact in the average scenario for Esino River (summer season)

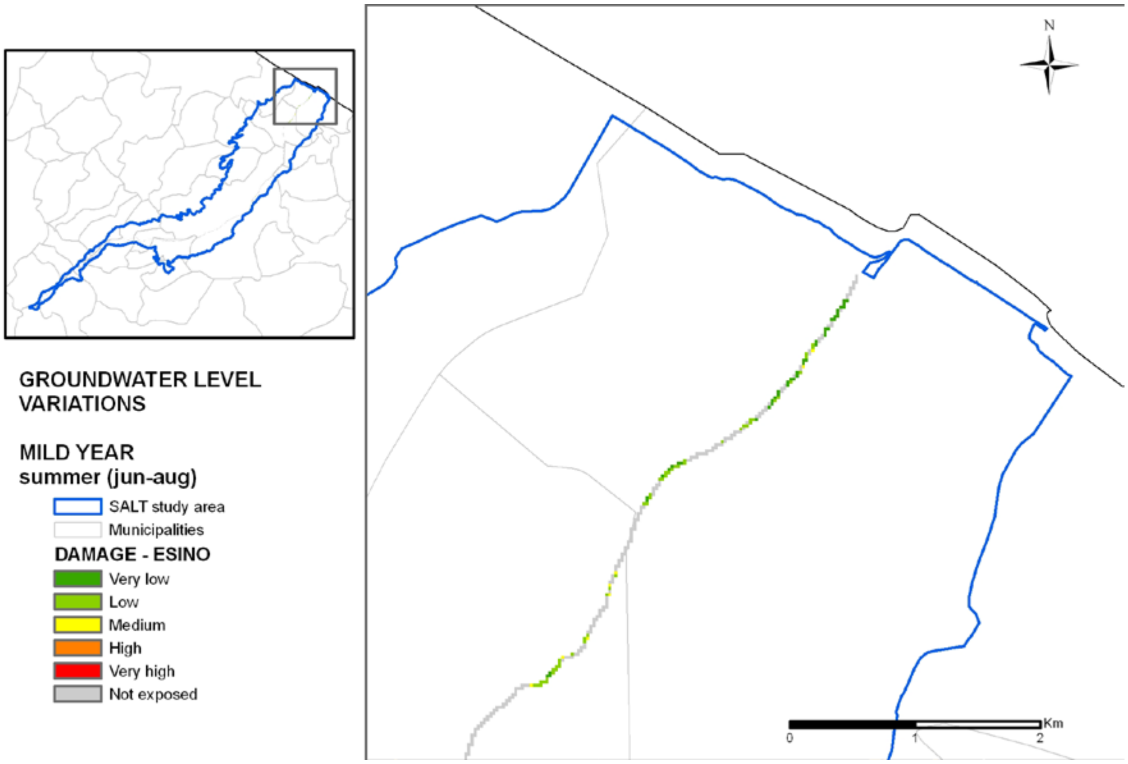


Figure A1.15. Damage map from GLV impact in the average scenario for lakes (summer season)

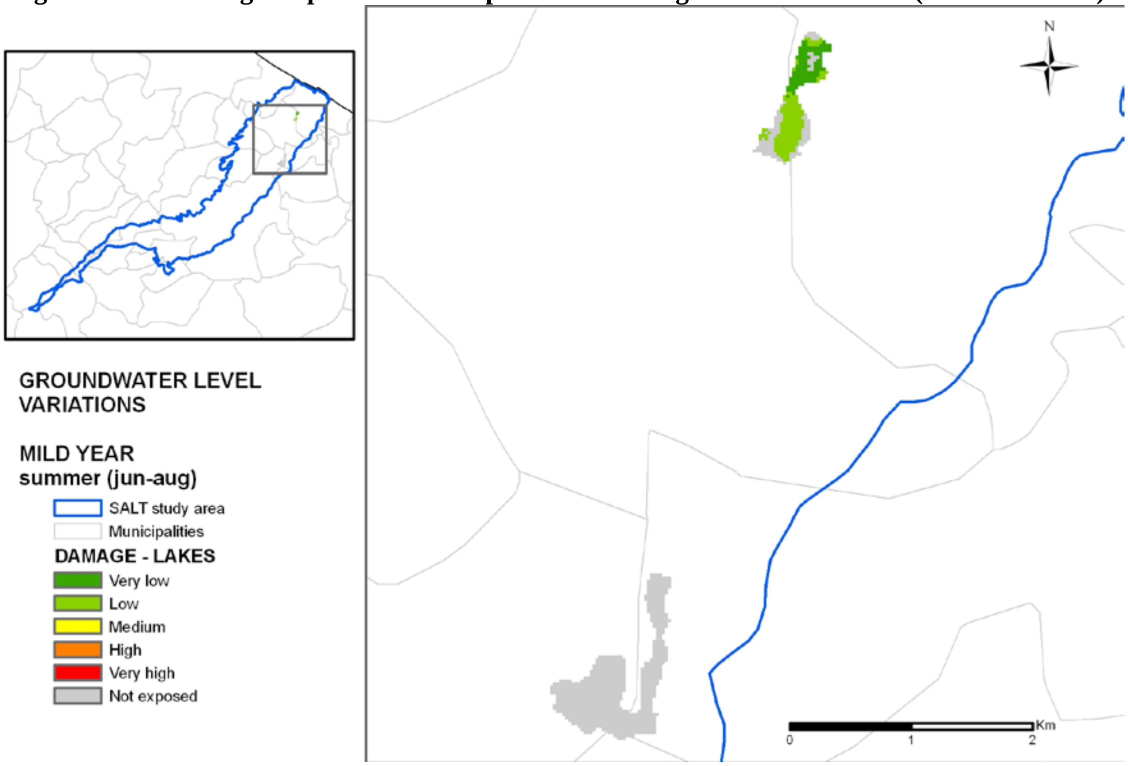


Figure A1.16. Damage map from GLV impact in the average scenario for forests and semi-natural environments (summer season)

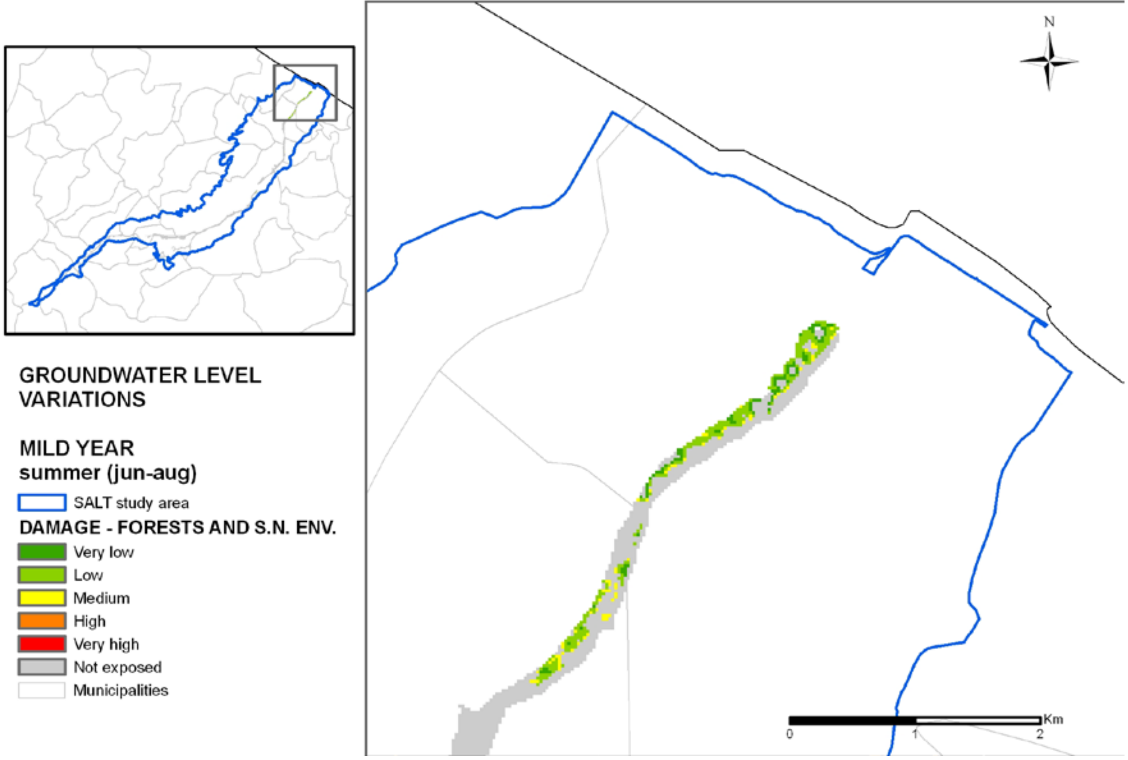


Figure A1.17. Damage map from GLV impact in the average scenario for agricultural areas (summer season)

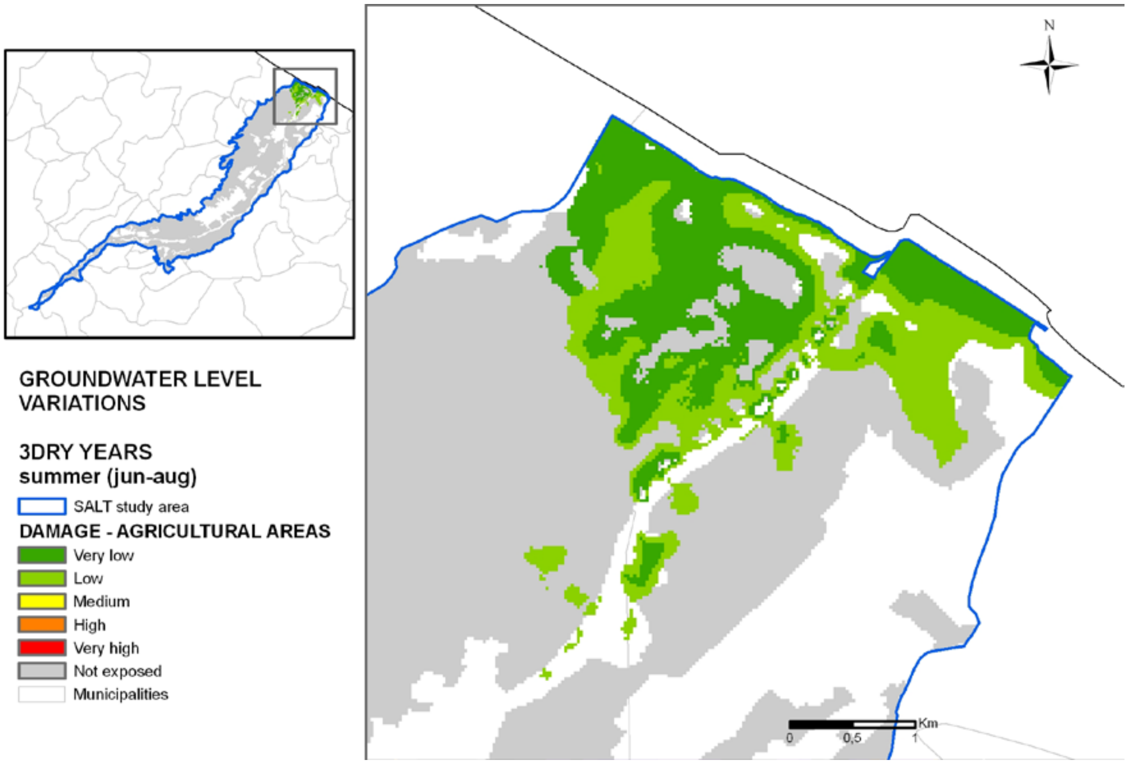


Figure A1.18. Damage map from GLV impact in the average scenario for Esino River (summer season).

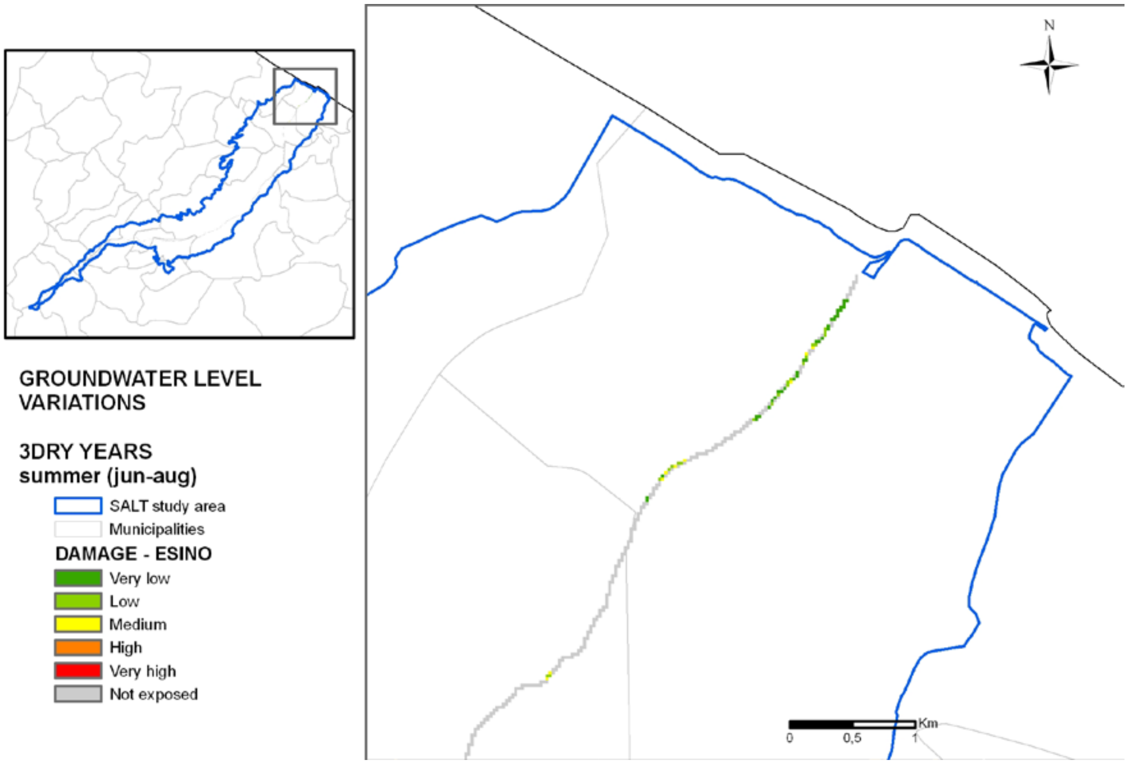


Figure A1.19. Damage map from GLV impact in the average scenario for lakes (summer season).

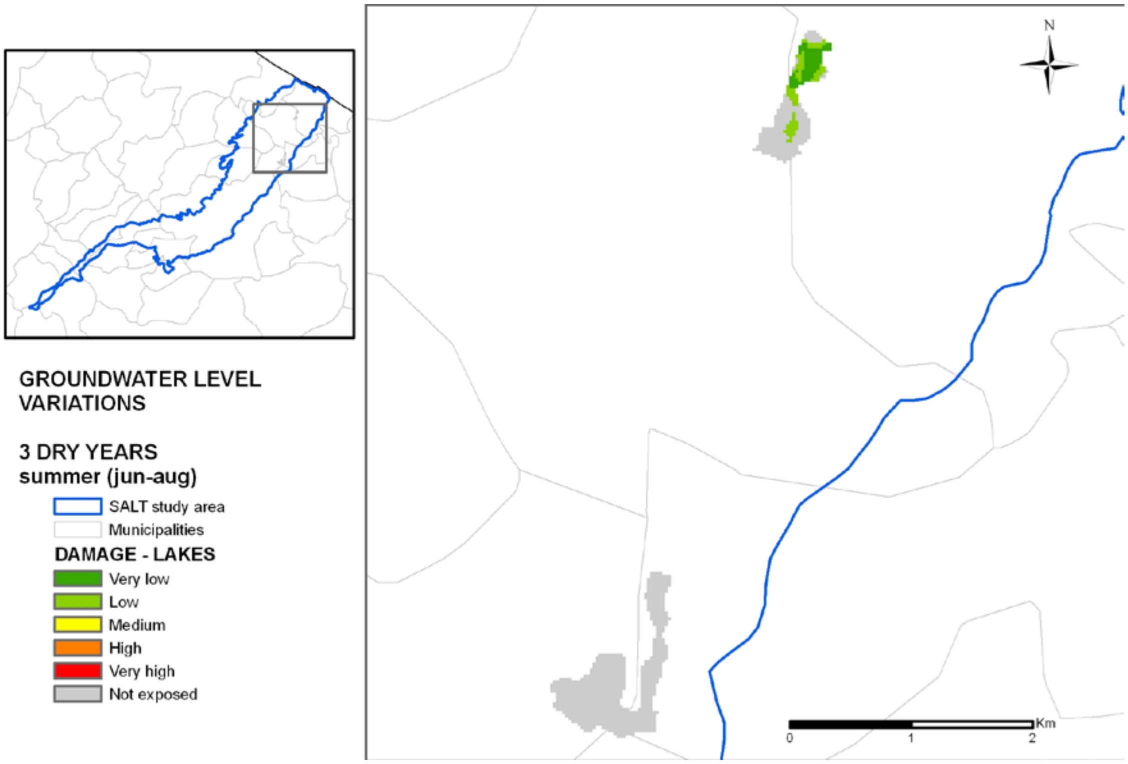


Figure A1.20. Damage map from GLV impact in the average scenario for forests and semi-natural environments (summer season).