Vulnerability of water-food-environment nexus at coastal areas under climate change

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Abstract
The management of deltaic areas requires a multidisciplinary approach since irrigated agriculture, fish farm industry, touristic activities and environmentally protected areas are conflicted water users. The present study aims at investigating the vulnerability of the water-food-environment nexus in the Mediterranean coastal zone under climate change conditions by initiating: a) the coupling of numerical models dedicated to the simulation of basins' rainfall-runoff, maritime hydrodynamics (coastal sea levels and currents) and physical characteristics of coastal waters, and b) the integration of climate change projections derived from a regional climate model (RCPs 4.5 and 8.5) to the aforementioned models. The produced river discharges and coastal waters' characteristics such as sea level elevations, flood volumes and seawater temperature/ salinity, are evaluated based on the current hydrosystem water demands and the exposure of the nexus to climate change is quantified.

Keywords: *water-food-environment nexus; numerical simulation; climate change; water resources management; integrated coastal zone management.*

1. INTRODUCTION
Recent projections by both general circulation models (GCMs) and regional climate models (RCMs) show that future climate will be characterized by monthly net rainfall decrease during winter and potential evapotranspiration increase during summer due to global warming. These climatic alterations will vary from one region to another, but many densely populated countries would be seriously affected. All expected climate change (CC) scenarios as defined by IPCC AR5 report [1] will induce a permanent stress on surface/subsurface water levels due to higher demands coupled to water resources shortage. It is also expected that the Mediterranean region will be among the areas that will be most affected by CC [2]. Indeed, this region currently faces major challenges and serious water issues arise, regarding sustainable water resources management and allocation of available water among competitive, i.e. domestic, agricultural, industrial, environmental, users. CC and climate variability can increase the risks and costs of water resources management, lead to quantitative and qualitative degradation of water resources, and subsequently influence socio-economic vulnera-

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bility and environmental sustainability.

Because of the notable interdependencies between water resources, energy production and provision of food, the so called "Nexus approach" proposes a new concept on the Integrated Water Resources Management approach. Moreover, the nexus approach "increases the understanding of the interdependencies across water, energy, food and other policies such as climate and biodiversity" [3]. Consequently, actions undertaken in one of the aforementioned sectors have imminent impacts to all others, therefore making the a-priori identification of these linkages to be of great importance in order to help target synergies and avoid potential tensions [4].

Deltaic regions and areas downstream of river basins usually are of relatively low elevation, and thus are known to be vulnerable to the impact of elevating sea levels in coastal waters due to climate change effects, *i.e.* either extreme storm surge events in short-term or mean sea level (MSL) rise in long-term [5]. As far as surface water resources in river delta areas is concerned, there are numerous studies about storm-induced sea level impacts on them. Authors of [6] investigated the responses of coastal wetlands with salt marsh ecosystems to rising sea levels. Authors of [7] emphasized the increased risk due to the concurrent occurrence of storm surge and river discharge extremes for the Rhine delta. The authors of [8] studied the sea-related natural hazards and related coastal risks of the Nile delta due to current and future CC by hydrodynamic simulations and observations of recent surge levels in the Mediterranean Sea in coastal areas of Egypt. Moreover, [9] showed that CC-driven storm surge inundation of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain pose significant flood risks. Specifically for the Mediterranean Sea, research about climate-related storm impacts on flooding of deltaic areas is rather limited [10].

The objective of the proposed research is the identification of climate change impact on water resources of Mediterranean coastal zones, as well as the implication these impacts pose to socio-economic vulnerability and sustainable development. To this end, numerical models related to surface dynamics, seawater intrusion, coastal circulation and optimization of water abstraction are developed and implemented, with emphasis on a novel computational multiscale approach for efficient water resources management as attributed by "water-food-environment" nexus. Finally, an integrated decision support and management model will be developed, providing sustainable solutions to water availability problems, enhancing decision making and supporting the implementation of effective management policies.

2. MATERIALS AND METHODS

For the achievement of the research aim, namely the investigation of vulnerability of nexus at coastal areas under climate change conditions, the development of a conceptual modelling framework that can simulate in a simplified, yet accurate manner the main processes inside the coastal zone is proposed as the principal methodological approach. Thus, the integration of the three larger-scale modeling components, as depicted in Figure 1, is proposed:

- Atmosphere: climatic data of atmospheric parameters (e.g. winds, sea level pressure, precipitation, temperature, etc.) are used, deriving from RCM implementations under two Climatic Scenarios (CS) based on Representative Concentration Pathways (RCPs) for greenhouse gas concentration trajectories in the 21st century [1].

- Land: a hydrological model is applied to assess freshwater availability, evaluate irrigation and environmental water demand coverage and quantify inflows form the river catchment to the coastal zone.
- Sea: two barotropic models for hydrodynamic circulation are developed producing depth-averaged currents and Sea Level Height (SLH) fields on the entire Mediterranean coastal zone scale of implementation, and moreover seawater physical parameters on the local coastal zone scale of the study area of focus.

2.1 Case study area

The proposed methodology will be applied in the Greek part of Nestos River (located in Northern Greece), a transboundary river basin whose catchment area geographically also belongs to Bulgaria by 50%. The river water is used for multiple purposes, since the surface runoff is exploited for power production (two existing and one under design hydropower plants), for covering irrigation demands in the deltaic area, and for environmental purposes. Moreover, the agricultural drainage channels in the west side of the delta are connected to a series of coastal lagoons (8 in total) that are separated from the sea with narrow sand bars and are used for intensive fish farming activities. The regional economy is based mainly on agriculture, tourism and fishery. In environmental terms, the Nestos delta is a very important habitat that has been declared as Ramsar site (10593 ha), as Special Protection Area (10000 ha) as well as Specially Protected Mediterranean Area.

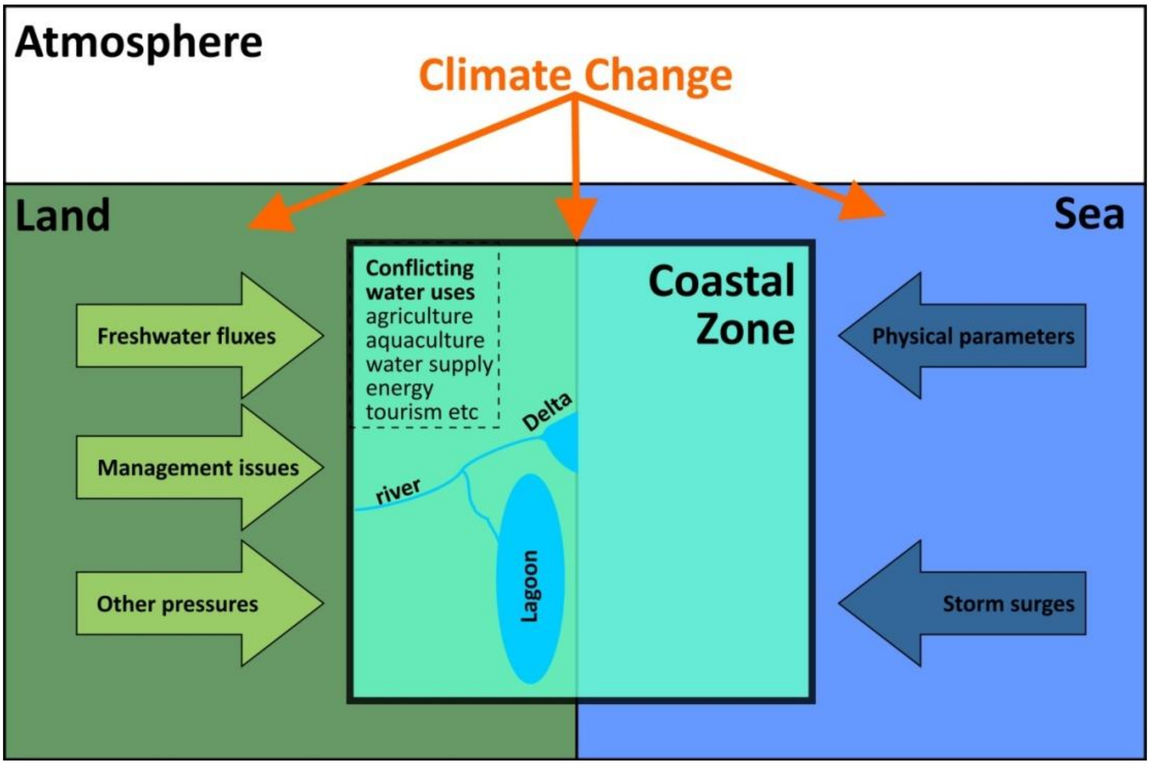

Figure 1. Conceptual diagram of modeling levels focusing at the coastal zone activities.

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2.2 Numerical models

The numerical models' implementation comprises two different but interconnected simulation fields. Particularly, Water Consumption Scenarios (WCS), focusing on future water/irrigation needs, changes in land-uses, etc. will initially be defined and thereafter will be coupled with climate change atmospheric datasets, in order to assess the future freshwater fluxes to the coastal zone (at the river estuary and lagoons) for all possible combinations of CS and WCS.

2.2.1. Hydrological models

The freshwater volumes that are concentrated in the case study's river basin and thereafter discharged into the sea will be simulated with the MODSUR (MODelisation du SURface) [11] hydrological model. It is a spatially distributed model, hence is based on a densely spaced grid and uses a progressive quadtree structure with varying cell sizes. The water budget in the MODSUR model is computed in each grid cell using a system of four reservoirs [12] responsible for the repartition of rainfall water into runoff, infiltration and evapotraspiration. All the parameters for the reservoirs are defined by the user on the basis of the physical and topographic characteristics of the basin such as the geology, land cover, land use and topography. Knowing the daily precipitation, temperature and potential evapotraspiration over the basin, the model computes the surface discharges on pre-selective cells that attribute the river network. The MODSUR model has been applied to the Nestos basin [13], with its calibration and validation periods ranging from 1987 to 1993 and from 1994 to 1995, respectively. In the presently proposed research, the parameterization of the model remains the same and alterations only concern input variables as derived by new implementations of the RCMs under medium to highly pessimistic RCPs. For that purpose, the gridded climate variables will be superposed over the hydrological model grid and their nesting in the MODSUR grid will be achieved with the use of spatial analyst tools.

2.2.2. Maritime hydrodynamic models

The numerical models for the simulation of maritime hydrodynamics also comprises two nested simulation fields: *a*) the global scale analysis of the entire Mediterranean basin in terms of storm-induced SLH and barotropic currents on the coastal zone, and *b*) the regional scale of the coastal study area pertaining the Nestos river Delta, local estuaries and adjacent lagoons.

Level *a* of implementation will be based on the MeCSS (Mediterranean Climatic Storm Surge) model [14], which is a 2-D horizontal, barotropic, hydrodynamic circulation model for high-resolution simulations of storm surges and related flows in large-scale, enclosed or semi-enclosed water bodies. MeCSS simulates the meteoro-logically induced sea-surface variations and depth-averaged currents by taking into account the atmospheric forcing (*i.e.* wind vector fields at 10 m from MSL and sea level pressure fields), the geostrophic effects of the Coriolis force, the influence of astronomical tides, bottom friction on the ocean bed, and internal shear forces due to horizontal eddies based on the eddy viscosity concept and the Smagorinsky model approach [15].

Level *b* of implementation will be based on the 2-D version of the TELEMAC software [16] that calculates free surface flows in natural coastal water bodies and estuaries and will serve as a Regional Coastal Circulation Model (RCCM). TELEMAC-

2D solves the two-dimensional shallow water flow equations based on finite element techniques operating on unstructured grids of triangular elements. It is particularly adapted to study water movements in shallow aquatic domains: coastal areas, estuaries, and rivers. It takes into account nonlinear effects of processes such as bed friction, geostrophic influence of Coriolis force, meteorological forcing (atmospheric pressure and winds), horizontal turbulence, torrent and river flow discharges, influence of horizontal temperature and salinity gradients on water density, wet-dry area estimation in the computational domain, intertidal flows on flat domains and flood plains, and current entrainment and diffusion of tracers with source and sink terms.

The RCCM will use all available data from the CS database, as well as freshwater fluxes at the Nestos delta to provide seawater salinity, temperature, and density, together with regional estimations of currents and SLH fields in each CS and WCS combination (Figure 3).

2.3 Climate change

In the proposed research, the climate data are based on two representative RCPs scenarios, out of the four available for the 21st century in IPCC-AR5, namely RCP4.5 and RCP8.5. The first one describes a possible climate future that depends on "modest" estimations about greenhouse gas concentrations in coming years, while the latter poses a "worst case scenario". Datasets used as input in these simulations were retrieved from the Med-CORDEX database (COordinated Regional Climate Downscaling EXperiment) dedicated to the Mediterranean. Several subsets/domains that include data derived by simulations combining various spatial resolutions (down to 10 km), and numerous combinations of GCMs, RCMs and RCPs, are stored in Med-CORDEX database which is currently and continuously updated.

Considering restrictions in completeness of datasets, as well as the types of input data needed by the hydrodynamic circulation and hydrological models, we were led to the selection of the MED-44 domain (Table 1), which covers the entire Mediterranean basin with a spatial resolution of 0.44° in a rotated-pole projected geographic system.

Table 1. MED-44 CORDEX domain geographic specifications

CORDEX Area	Name	Grid spacing, position of rotated North Pole (NP) and outermost cell centers in rotated coordinates (°)								
		Degrees (°)	NP lon	NP lat	N lon	N lat	West	East	South	North
Mediterranean	MED-44	0.44	198.0	39.25	98.00	63.00	-23.22	19.46	-21.34	5.

The original MED-44 data were further processed by the means of the Climate Data Operators tool set (https://code.mpimet.mpg.de/projects/cdo/), in order to match the requirements of the study's simulations (Table 2) and validation against the CERA-Interim dataset [17].

Table 2. Study domains geographic specification

Study Area	Name	Grid spacing and outermost cell centers in regular lon-lat coordinates (°)				
		Degrees (°)	West	East	South	North
Mediterranean	MED-Sea	0.1	-7.00	36.00	30.25	45.75
Nestos river coastal area	Nest-Sea	0.1	24.30	25.1	40.70	41.10
Nestos river basin	Nest-Hydro	0.1	23.30	25.00	40.80	42.20

2.4 Socioeconomic assessment

For the assessment of the deltaic area socioeconomic status and its dependence on future climatic variations, the activities taking place inside the study area should be studied and analyzed in detail. The quantified simulation results will be inserted as input into a custom developed decision support and management model and several coastal aquifer management scenarios as well as the nexus equilibrium will be investigated. The specific data include available water flows for irrigated agriculture, environmental discharges for covering the minimum ecological flows requirements, potentially flooded areas both from fresh and sea waters, sea level highs, as well as sea water physical characteristics. The investigated scenarios include the implementation of alternative management practices, such as changes in agricultural patterns within the river basin, application of alternative irrigation methods, generation of energy from different sources, changes in activities spatial planning or even changes in activities and land uses.

Furthermore, the stakeholders related to the aforementioned activities should be reported, since they play a more or less important role in decision making. The key stakeholders preference and water users' position on issues regarding the delta will be also taken into account, within a multicriteria model developed in parallel with the management model. The alternative management scenarios will be evaluated based on environmental, social and economic criteria, while PROMETHEE methods [18] will be used in order to find the optimal managerial solution.

3. EXPECTED RESULTS AND DISCUSSION

3.1 Scientific Benefits

Freshwater input is an important parameter to thermohaline coastal circulation. The comparison of climatic simulation results from models of intermediate complexity up to fully coupled atmosphere–ocean general circulation models, demonstrated that thermohaline circulation is highly sensitive to riverine freshwater fluxes [19]. Past literature has mostly focused on numerical studies that use regional [20] hydrodynamic circulation models in open sea and coastal environments to investigate future sea-level trends, as well as climatic applications of hydrological models [21]. However, limited studies include coupled or de-coupled applications of hydrodynamic ocean circulation and hydrological models for climate studies; most of them are focused on atmospheric-ocean or atmospheric-hydrologic model coupling under CC. [22] deal with the subject of concurrent modelling of hydrology and ocean circulation; they include the assessment of the impacts of climate change, of related projected land-use changes and of sea level rise to the Snohomish river estuary, using coupled watershed hydrologic and estuarine hydrodynamic models, focusing on changes of river flow, estuarine salinity and hydrodynamics.

The proposed research work deals with an original, interesting and challenging field. Particularly, it is proposed to integrate the three basic modelling levels of implementation (atmosphere-sea-land) in order to build a unified modelling procedure that can robustly estimate the response of the coastal zone and especially of the river mouth and coastal lagoon system to future climate conditions. Main benefits include: a) the development and testing of novel tools for coupling climate, eco-hydrology and seawater intrusion models for sustainable water resources management in coastal areas; b) the introduction of novel applications for the concurrent modelling of hydrologic parameters and coastal ocean dynamics (circulation and sea level) under climate change scenarios; c) the development of an Integrated Coastal Zone Management (ICZM) tool for the evaluation of aqua-farming under CC applied to selected sites; d) the development of appropriate databases linked to GIS systems for field sites data that will be available for Mediterranean partners; e) the determination of optimal conditions for joint use of surface/groundwater or artificial recharge and aquifer water management under CC-induced stresses.

The proposed integrated water management and decision support model aspires to contribute to regional scientific enhancement in many ways, as it will enhance the research capacity, knowledge and skills of local research organizations and institutions by shedding light on and facilitating decision-making processes regarding the water-food-environment nexus in northern Greece. The novel methodology that will be developed is related to the combined management of water resources, land use and human activities on the basis of a multicriteria approach and is going to identify optimal solutions in a complex multi-criteria environment, i.e. solutions technically and cost efficient, as well as environmentally responsible and socially acceptable. The proposed work-data flow presented in Figure 2 depicts the challenge as well as the power of modelling coupling in order to support complex decision making, usually observed in water management studies.

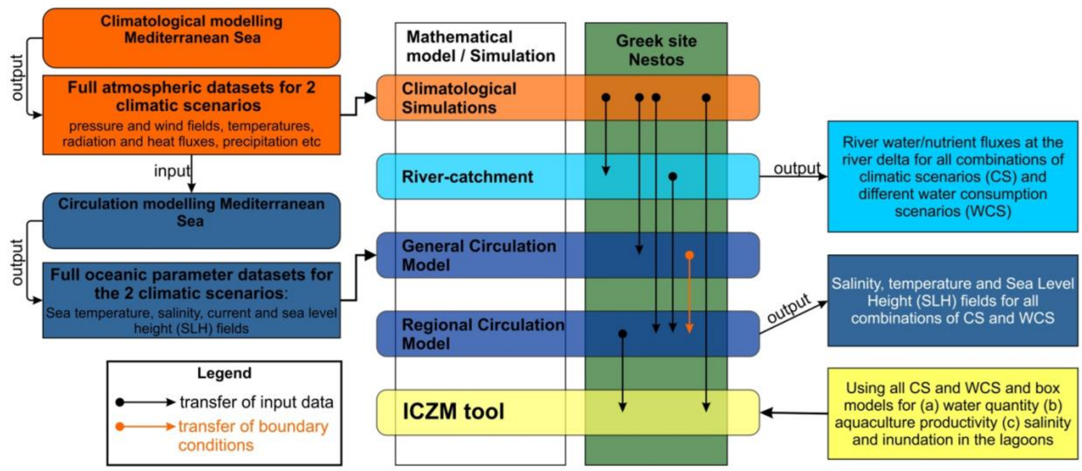

Figure 2. Methodological framework

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3.2 Technological innovations and support of regional socioeconomic activities

The technological benefits deriving from the proposed research include the improvement of existing models in terms of one-way coupling between them and necessary calibration, in order to cooperate with each other optimally. The merging of these two domains, i.e. inland waters and sea, is conducted in the coastal zone where the application of new technologies facilitates the development of the ICZM tool dedicated to the management of the coastal zone. The coupling of different perspective models, i.e. hydrologic and maritime hydrodynamic simulation models with management and decision support tools, under variable climatic conditions driven by CC is considered as a rather intriguing challenge, and thus requires special "programming bridges" in order to succeed such an integration.

The projected social benefits of the proposed study to the local community are also significant, since one of the objectives of the research is to formulate an ICZM tool that can be easily used by local institutions and stakeholders to assess the impacts of both future climate conditions and management practices to the river nexus. The main goal of the developed ICZM tool is to urge regional and/or central authorities to: a) assess future impacts of management policies or practices on the sustainability of the coastal area under study in environmental and socioeconomic terms, b) aid the evaluation process and define the optimal sustainable management decision, which is vital and rather beneficial to the local community. Very crucial part of the developed model is the deliberation process. The stakeholders and local community will be directly involved and included, providing important information for the identification of management problems/issues of the area and quoting their point of view on the proposed alternative management practices.

3.3 Societal, environmental, and economic benefits

The proposed research follows an integrated vision dealing with issues that will have important social, economic and environmental repercussions, i.e. impacts on the water-energy-food nexus. Since water is probably the most precious resource in Southern Mediterranean countries, any methodology that can contribute to more efficient analysis, control and use of the coastal aquatic resources will have positive impacts on local citizens. It will hopefully allow in particular to: a) achieve sustainable development; b) meet the real needs of local inhabitants of coastal zones especially those suffering from scarcity of water and climate change; c) improve the environmental context by the added value of water resources management and control; d) increase water availability through seawater intrusion control and artificial recharge (including water reuse); e) render the water resources professionals (managers, planners and engineers) in targeted areas of the Mediterranean Sea’s coastal zone as immediate beneficiaries.

4. CONCLUSIONS

The proposed research conclusively intends to offer solutions in designing a problem solving platform that integrates and utilizes quality datasets distributed across different organizations, to monitor and analyse environmental states and dynamics, through aggregated time-dependent geo-statistical descriptors in a regional (Mediterranean coastal zone) and local perspective (Nestos river delta and coastal area in northern Aegean Sea, Greece). This way a new generation of environmental management systems is promoted particularly targeting at technological gaps of integrated modelling for coastal waters, estuarine and riverine domains. Improvements in local and regional hydrological prediction, monitoring and management systems are guaranteed through novel applications of integrated coastal water resources management. Therefore, integration of expertise, data and knowledge to build regulatory actions concerning water quality issues abatement are fostered. To sum up, effective environmental management is secured via integration of natural, social, political, economic, and governance factors and by providing a holistic framework to achieve sustainable outcomes. Active involvement of stakeholders, municipalities and institutional actors is also promoted to collate resources, ideas and synergies.

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