Towards co-management of Gialova Lagoon

A Natura 2000 coastal wetland in Messinia, Greece

Georgios Maneas
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Abstract
The management of Natura 2000 sites is considered as the cornerstone for the conservation and restoration of biodiversity within Europe. However, protected ecosystems provide a plethora of benefits to local societies, and support the local economy. Thus, to seek solutions for complex environmental issues within Natura 2000 sites it is imperative to approach the site of concern as a connected social-ecological system, and to strengthen the participation of stakeholders in decision-making following a co-management approach.

Gialova Lagoon wetland, in Messinia, Greece represents an example of Natura 2000 site which needs to be managed. The overall aim of the PhD thesis was to assess the problem of lagoon salinization, and provide policy recommendations for wetland restoration and management of associated freshwater resources under a changing climate. The thesis has followed a social-ecological approach, by integrating DPSIR framework with participatory Systems Dynamic modelling and the concept of ecosystem services. Knowledge gaps about major social and ecological components were assessed by applying a variety of methods, namely (a) field monitoring and observations, (b) GIS analyses, (c) consultation with stakeholders, (d) modelling and scenarios.

The thesis results suggested that past human interventions had multi-fold effects on the Gialova Lagoon wetland, namely hydrology alteration, ecosystem fragmentation, loss and transformation of natural habitats. Furthermore, the combined effects of alterations in hydrology and climate change have led to increased salinity in the wetland over time. These alterations had profound implications on wetland ecosystem services such as the diversity of habitats and waterbirds and the provision of fish. Under contemporary hydrological connectivity and on-going climatic conditions, the mean annual salinity of the lagoon has increased from approximately 35 g/L during the period 2016-2018 to approximately 40 g/L during the period 2021-2023 indicating a salinization increase of approximately 1 g/L per year.

To identify restoration alternatives, the work under the PhD thesis has engaged scientists with local stakeholders from the sectors of agriculture, fishing, tourism, and public administration, in a co-management approach. The end product, an SDM (Systems-Dynamics model) co-created with stakeholders, was suitable for exploring scenarios for salinity regulation and management of associated freshwater resources, under a changing climate (RCP 4.5). The derived management suggestions, namely restoration of the connectivity with the surrounding freshwater bodies (river, artesian springs) and between habitats (e.g., lagoon-marshes), could result in the de-salinization of the lagoon within a 10-year period, and could be applied within the Natura 2000 framework as they consider social and ecological needs (e.g. enhancement of biodiversity and fish production). However, under current abstraction rates for irrigation and municipal water-supply, there is a high risk of groundwater scarcity during years with dry conditions, and thus investments in water-saving technologies (e.g. smart irrigation) should be promoted to ensure adequate water availability for restoration, and enhanced resilience of the local economy against groundwater scarcity.

Keywords: Salinity, wetland restoration, ecosystem services, participatory modelling, social-ecological system.

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To my family & friends.
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SAMMANFATTNING

Med tanke på den pågående förlusten av Europas biologiska mångfald börjar det bli allt mer angeläget att uppfylla de ambitiösa skydds- och återställandemålen i EU:s strategi för biologisk mångfald genom en förbättrad förvaltning av skyddade områden inom EU:s Natura 2000-nätverk. För att förbättra tidigare förvaltningsmetoder, som har ansetts vara o tillräckliga för att möta lokala behov, och för att ta itu med komplexa miljöfrågor, finns det ett behov av att betrakta påverkade områden som kopplade social-ekologiska system och engagera intressenter i beslutfattande. Detta behövs särskilt i avseende på förlust av våtmarker i kustområden, eftersom deras restaurering och förvaltning uppvisar en dynamisk komplexitet och kräver ett holistiskt tillvägagångssätt som integrerar sociala, ekonomiska och ekologiska aspekter i både rum och tid.

Gialova-lagunens våtmark i sydvästra Grekland är ett exempel på ett naturligt kust-ekosystem som har försämrats på grund av en svag förvaltning under de senaste sju decennierna, och där restaureringsåtgärder har misslyckats i praktiken. Det övergripande syftet med den här doktorsavhandlingen var att utvärdera problemet med en ökad salthalt i lagunens vatten och att bidra med rekommendationer för hur våtmarken kan återställas genom en förbättrad förvaltning av tillhörande sötvattenresurser under ett föränderligt klimat. Avhandlingen har följt en systemansats och har integrerat ett DPSIR-ramverk med deltagande System Dynamisk modellering och analys av förändrade ekosystemtjänster. Kunskapsluckor om viktiga sociala och ekologiska komponenter har utvärderats genom att använda en mängd olika metoder, nämligen (a) fältmätningar och observationer, (b) GIS-analyser, (c) samråd med intressenter, (d) modellering (numerisk och systemdynamisk) och Scenarier.

Resultaten visar att tidigare ingrepp har haft flera olika effekter på Gialova-lagunens våtmark, såsom fragmentering av ekosystem, förlust och omvandling av naturliga livsmiljöer, där den kombinerade effekten av människans ingrepp och klimatförändringar har lett till ökad salthalt i våtmarken över tid. Dessa förändringar har haft stora konsekvenser för våtmarken och dess ekosystemtjänster, såsom förlust av habitat, fåglar och fisk. Under rådande vattenflöden och klimatförhållanden har den genomsnittliga årliga salthalten i lagunen ökat från cirka 35 g/L under perioden 2016–2018 till cirka 40 g/L under perioden 2021–2023, vilket indikerar att salthalten har ökat med cirka 1 g/L per år. För att utvärdera olika förvaltningsalternativ, har denna doktorsavhandling uppmuntrat ett brett deltagande av en mängd lokala intressenter från olika sektorer, såsom jordbruk, fiske, turism, offentlig förvaltning och andra Institutioner/NGOs. Detta har resulterat i utvecklandet av en gemensam System-Dynamisk modell som kan användas för att utforska alternativ för hur man kan reglera lagunens salthalt samt tillhörande sötvattenresurser, under ett föränderligt klimat (RCP 4.5).

Modellresultaten antyder att en minskad fragmenteringen av vattnetillgången i våtmarken (lagun-kärr) och en gradvisa återställandet av förbindelserna mellan våtmarken och de omgivande sötvattenförekomsterna (yt och grundvatten) kan resultera i en avsaltning av våtmarken inom en 10-årsperiod. Under nuvarande uttagningshastigheter för bevattning och kommunal vattenförsörjning visar modellresultaten att det finns en hög risk för en överanvändning av det permanenta beståndet av grundvattnet under år med torra förhållanden, varför investeringar i vattenbesparande teknik (t.ex. smart bevattning) bör främjas för att öka områdets motståndskraft mot minskat grundvattenförråd.
Οι διαχείρισεις των περιοχών Natura 2000 αποτελείει ακρογωνιαίο λίθο για την προστασία και την αποκατάσταση της βιοποικιλότητας στην Ευρώπη. Ωστόσο, εκτός από τον βασικό αυτό ρόλο, η προστασία της οικοσυστήματα προσφέρει πληθώρα υπηρεσιών στις τοπικές κοινοτίες, συμβάλλοντας στην υποστήριξη και την ανάπτυξη της τοπικής οικονομίας. Επομένως, για την αντιμετώπιση πολύπλοκων περιβαλλοντικών ζητημάτων εντός των περιοχών Natura 2000 και για την επίτευξη αειφόρου διαχείρισης των φυσικών πόρων, είναι ζωτικής σημασίας η προσέγγιση της περιοχής ως ένα συνδεδεμένο κοινωνικο-οικολογικό σύστημα. Συγκρότηση, πρέπει να ενισχυθεί η συμμετοχή των ενδιαφερόμενων φορέων στη λήψη αποφάσεων, ακολουθώντας μια προσέγγιση συν-διαχείρισης. Η Λιμνοθάλασσα της Γίαλοβας (Μεσσηνία, Ελλάδα) αποτελεί ένα παράδειγμα φυσικού οικοσυστήματος εντός του δικτύου Natura 2000 που χρειάζεται διαχείριση. Ο κύριος στόχος της διδακτικής διατριβής ήταν η αξιολόγηση του προβλήματος της αλατότητας, καθώς και η διερεύνηση προτάσεων αποκατάστασης του υγροτόπου, λαμβάνοντας υπόψη τη διαχείριση των διαθέσιμων πόρων γλυκού νερού, υπό το πρίσμα της κλιματικής αλλαγής. Η διατριβή ακολούθησε μία κοινωνικο-οικολογική προσέγγιση, συνδυάζοντας το πλαίσιο DPSIR με συμμετοχικές διαδικασίες μοντέλοποιησης και την έννοια των οικοσυστημάτων υπηρεσιών. Η συλλογή δεδομένων πραγματοποιήθηκε μέσω διαφόρων μεθόδων, περιλαμβανομένων (α) καταγραφών στο πεδίο, (β) εφαρμογής γεωγραφικών συστημάτων πληροφοριών, (γ) διαβούλευσης με ενδιαφερόμενους φορείς και (δ) μοντέλοποιησης με σενάρια. Η δημιουργία προτάσεων αποκατάστασης βασίστηκε στην επικοινωνία μεταξύ ερευνητών και ανθρώπινου παραμετρού των τοπικών κοινοτήτων (περιοχές, εθνικές, διεθνείς) και την προσέγγιση συν-διαχείρισης. Το τελικό προϊόν των διαβουλεύσεων, ένα SDM (μοντέλο δυναμικής της συστήματος), το οποίο δημιουργήθηκε σε συνεργασία με τους ενδιαφερόμενους φορείς, εφαρμόστηκε για τη διερεύνηση σεναρίων προς την κατεύθυνση αλλαγής της αλατότητας, υπό το πρίσμα της κλιματικής αλλαγής (κλιματικό σενάριο RCP 4.5). Τα αποτελέσματα του διαλόγου δείχνουν ότι η αποκατάσταση της συνδεσιμότητας του υγροτόπου με τα επιφανειακά ύδατα (ποτάμι, πηγές), καθώς και η διερεύνηση προτάσεων μεταξύ οικοτόπων εντός του υγροτόπου (λιμνοθάλασσα-βάλτοι), θα μπορούσαν να οδηγήσουν στη μείωση της αλατότητας στη λιμνοθάλασσα εντός 10 ετών. Δετόσο, η ανεξέλεγκτη αντλήση υπόγειων νερών (άρδευση, ύδρευση) αναμένεται να προκαλέσει πιέσεις στους διαθέσιμους υδάτινους πόρους. Επομένως, προτείνεται να η πραγματοποίηση επενδύσεων σε τεχνολογίες εξοικονόμησης νερού (p.χ. έξυπνη άρδευση, βελτίωση δικτύων ύδρευσης), με στόχο να διασφαλίζεται η επαρκής διαθέσιμότητα νερού για την προστασία του υγροτόπου και να ενισχυθεί η ανθεκτικότητα της τοπικής οικονομίας έναντι της λειψυδρίας.
LIST OF PAPERS

This doctoral thesis consists of a summary and four appended papers (referred to as Paper I - IV) listed below:


AUTHOR CONTRIBUTIONS

I  Conceptualization, study design and methodology: GM, DB, HB, and SM.
Data collection (fieldwork) and analysis: GM and EM.
Interviews with stakeholders: GM.
GIS software: EM.
Visualization: GM, EM and DB.
Supervision: HB and SM.
Writing – original draft preparation: GM.
Writing – review and editing: GM, HB and SM.
All authors discussed the content, provided feedback and wrote the final paper.

II  Conceptualization and study design: SM and SWL.
Methodology and model development: SM and SWL with feedback from GD.
Historical data collection and analysis: GM.
Provision and analysis of meteorological data: BEP.
Writing – original draft preparation: SM.
Writing – review and editing: SM with support from GM, SWL and GD.
All authors discussed the content, provided feedback and wrote the final paper.

III  Conceptualization and study design: GM, DB, and HB.
Methodology: GM and DB.
Fieldwork, data collection and analysis: GM, DB and VN.
Writing–original draft preparation: GM.
Writing – review and editing: GM, DB and HB.
All authors discussed the content, provided feedback and wrote the final paper.

IV  Conceptualization and study design: GM, EK, APK and HB.
Methodology: GM, EK, APK, JLK and HB.
Model development: GM with support from EK, YP, PV and JLK.
Data collection and analysis: GM, EK and YP.
Group discussions with stakeholders: GM and EK with support from YP, EP and MP.
Writing—original draft preparation: GM with support from EK, APK and HB.
All authors discussed the content, provided feedback and wrote the final paper.
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<tr>
<td>CPUE</td>
<td>Catch Per Unit Effort</td>
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<td>Drivers-Pressures-State-Impacts-Responses</td>
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# Introduction

## 1.1 Mediterranean coastal lagoons

Coastal lagoons are transitional wetland ecosystems between land and sea, with a complex hydrology (Pérez-Ruzafa et al., 2020; Soria et al., 2022). The water body of a coastal lagoon is usually shallow, and is connected to the sea through one or more canals (Kjerfve and Magill, 1989). Water exchanges between the lagoon and the sea mainly occur because of tides, freshwater inflows (e.g., surface, groundwater), winds, and waves (Bengtsson, 2012; Pérez-Ruzafa et al., 2020).

Mediterranean lagoons may differ in typology and use, but collectively they support a plethora of habitats for many species, and play an important ecological role (Pérez-Ruzafa et al., 2011a; Cataudella et al., 2015). Lagoons provide a nursery and feeding ground for a variety of fish (Pérez-Ruzafa et al., 2011b), including species endemic to the Mediterranean (e.g. *Aphanius fasciatus*) and species with high nutrition and economic value like the Gilt-head sea bream (*Sparus aurata*) and the European bass (*Dicentrarchus labrax*) (Leonardos and Sinis, 1998; Algers et al., 2008; Cataudella et al., 2015). In addition, lagoon ecosystems are important habitats for waterbirds, as they are used as wintering, stopover (during migration), and breeding areas (Ramsar convention, 1994, art1.2; Warnock, 2010).

Coastal lagoons are hot-spots for biodiversity and source of multiple ecosystem services (ES) to communities (Newton et al., 2018; Rodrigues-Filho et al., 2023). For example, fisheries and various forms of aquaculture have been traditionally carried out in Mediterranean lagoons since ancient times, and are part of the cultural heritage (Cataudella et al, 2015; Soria et al., 2022). In managed, well-preserved lagoons, the development of outdoor activities (e.g. birdwatching, sport-fishing) provides opportunities for the development of Nature Based Tourism, the fastest growing tourism sector within Europe (CBI, 2021).

Despite their value, approximately 35% of the world’s wetlands were lost between 1970 and 2015, with an accelerating annual loss rate since 2000 (Courouble et al., 2021; UNCC, 2023). During the same period, the Mediterranean region has lost almost 50% of its wetlands due to rapid socio-economic and demographic development, poor wetland management, and lack of comprehensive policies (Trombetti et al., 2022), while the majority of remaining coastal lagoons is at an unfavourable poor or bad conservation (Soria et al., 2022; EU Habitat assessment, 2023; UNEP, 2023). Mediterranean lagoons are under pressure due to increasing water demand from agriculture and tourism, which reduce water availability for lagoon ecological systems (Pérez-Ruzafa et al., 2011a, 2019; Facca, 2020; Maes et al., 2020; Newton et al., 2020; Bray et al., 2022). In addition to decreasing runoff (e.g., Destouni and Prieto, 2018), climate change is expected to further reduce freshwater availability for ecosystems in the Mediterranean region due reduced precipitation and increased evapotranspiration (Gao and Giorgi, 2008; Cheval et al., 2017). Therefore, coastal areas in the Mediterranean (and wetlands in particular) are regarded as vulnerable to climatic changes (Gao and Giorgi, 2008; Klein et al., 2015).

Climate change, along with past and contemporary anthropogenic modifications of the hydrologic regime, and competing demands for freshwater resources, are considered the main reasons behind salinization, a widespread threat to the structure and ecological functioning of coastal wetlands that is currently occurring at an unprecedented rate and geographic scale (Herbert et al., 2015). In coastal lagoons, salinization has an impact on biochemical and ecological functioning, as it affects the cycle of major chemical elements, and biodiversity, since all biota have a specific tolerance to salt concentration (Lissner & Schierup, 1997; Leonardos and Sinis, 1998; Algers et al, 2008; Bernabò et al., 2013; Herbert et al., 2015; Tursi et al., 2023).
1.2 Natura 2000 network

The Natura 2000 network forms the backbone of EU’s conservation policy (European Commission, 2023a; European Commission, 2023b), and all member countries all obliged to designate and safeguard protected areas (PAs) following the guidelines of the EU’s Birds and Habitats Directives (EU’s Habitats Directive 92/43/EEC, 1992; EU’s Birds Directive 2009/147/EC, 2009). Within the EU, coastal lagoons are established as priority habitats for conservation and they are therefore included within the EU Natura 2000 network of protected areas (EU’s Habitats Directive 92/43/EEC, 1992). However, in several occasions they are also protected under the Birds Directive as they provide habitats for birds listed in the Annex I of the Directive, like herons, ducks and waders among others (EU’s Birds Directive 2009/147/EC, 2009).

The Natura 2000 is the world’s largest coordinated network of legally protected areas, (European Commission, 2023a). Nonetheless, recent reports have revealed that most Member States have faced challenges in managing their Natura 2000 networks (ECA, 2017; CEEweb, 2019). In contrast to initial ambitions, and despite the efforts, biodiversity loss remains one of the main environmental challenges within EU (ECA, 2017). Europe’s biodiversity continues to decline at an alarming rate, as more than 80% of habitats at EU level is at poor conservation status (EEA, 2023a). Habitats and species are under threat due to human activities (e.g. overexploitation and unsustainable management practices, water regime modification, pollution) and climate change, which is further reinforced by biodiversity loss (EEA, 2023a; EEA, 2023b; UNCA, 2023).

Greece provides an example of a Member State where the adoption of Natura 2000 framework has been unsuccessful, and in 2019 the European Commission decided to refer Greece to the European Court of Auditors over its failure to protect natural habitats and species adequately (European Commission, 2023c). The experience from the implementation of management actions within the Greek Natura 2000 sites has revealed that in most occasions the managers have followed an expert-based approach, with limited participation of local communities in the design process (Apostolopoulou et al., 2012; Tsianou et al., 2013). This approach has led to conflicts among associated stakeholders (SHs) which has delayed or even hindered restoration and management actions at the site level (Apostolopoulou and Pandis, 2010).

1.3 PhD rationale and aim

A typical example of mis-management within the Greek Natura 2000 network is the focus area of this thesis. The Gialova Lagoon (GL) site, has been among the first wetlands of the Greek Natura 2000 network, but similar to other Greek PAs, the management of the site has not been assigned to a designated management body until recently (OCG, 2020). The wetland has been ‘diagnosed’ with high salinity levels already at the end of the last century (Koutsoubas et al., 2000), but previous restoration efforts for halting salinization have faced challenges during implementation (HOS, 2000), although the suggestions were based on robust justification from research activities in the area (Arvanitidis et al., 1999; Koutsoubas et al., 2000). Similar to other examples in Greece (Apostolopoulou et al., 2012; Tsianou et al., 2013), biodiversity conservation was considered above local needs (e.g. fishing, agriculture, tourism), an approach which was proven insufficient in creating links between nature and human well-being, resulting to conflicts that eventually tackled the implementation of restoration efforts (Bousbouras et al., 2011).

The example of GL supports an argument from Kofinas (2009), according to which top-down (scientific) approaches in resources management can be insensitive and unresponsive to local needs, while they tend to ignore the range of social-ecological interactions that occur within an area of concern. From a social-ecological perspective, people depend on natural resources and benefits provided by the ecosystems while ecosystem dynamics are affected by human activities (Chapin et al., 2009; Kofinas, 2009). Although Natura 2000 site-managers must take conservation measures for restoring habitats and maintain protected
species at a favorable conservation status, socioeconomic activities are not prohibited within the PAs (ECA, 2017).

To that end, understanding current status and future trends requires a broad interdisciplinary framework that integrates concepts and approaches from natural and social sciences (Chapin et al., 2009), and engages different types of stakeholders (e.g., science, policy, business, citizens), following a co-management approach. In fact, the active involvement of local SHs in decision making around complex environmental issues which occur within Natura 2000 sites, is believed to increase environmental awareness and minimize emerging conflicts (Vokou et al., 2014). Thus, in addition to robust scientific knowledge, the successful management of Natura 2000 sites requires effective coordination between a wide range of sectors at a site level, namely the environmental, agricultural/fishing, public administration, and tourism sectors (ECA, 2017; CEEweb, 2019). This is particularly needed in the case of degraded coastal lagoon and wetland sites, as their restoration and management exhibit a dynamic complexity (Ghajarnia et al., 2020), which requires a holistic approach that integrates social, economic and ecological needs in space and time, and engages stakeholders in decision making (Bennich et al., 2020; Tomscha et al., 2021; Reeves and Bonney, 2023).

In view of the above, the overall aim of this thesis is to assess the problem of GL salinization and provide alternatives for wetland restoration under a changing climate, by following a social-ecological approach. The PhD work is based on a variety of concepts and methods, which allow for the integration of scientific knowledge and local expertise/needs into a decision-support-making-tool towards the environmental co-management of the GL Natura 2000 site. The thesis is developed around six research questions (RQ):

RQ1 Which are the major drivers behind wetland salinization and associated degradation overtime, and which are the contemporary pressures?

RQ2 Which is the magnitude of salinization risk under current conditions?

RQ3 What is the impact of human interventions and salinization on the wetland’s hydrology, ecology and associated ES?

RQ4 What type of restoration alternatives could be applied to cope with wetland salinization under a changing climate?

RQ5 How can suggested restoration alternatives support the efficacy of existing Natura 2000 management plans?

RQ6 How can stakeholders be engaged in decision making and promote environmental co-management of the GL Natura 2000 site?
2 Methods

2.1 A systems perspective

Overall, the thesis has followed a systems approach. To assess the problem of wetland salinization and mis-management of associated freshwater resources, the GL was considered as part of a wider social-ecological system (GL-SES) with interconnected components in space and time (section 2.2). A social-ecological system consists of natural elements (water, soil, organisms, etc.) and human activities which contribute to societal well-being, it has explicit boundaries and rules which depend on the problem and the objectives of the study, and it can be defined at multiple scales (Chapin et al., 2009).

The temporal analysis of social and ecological components within the GL-SES covered the period 1945 to 2100, and was divided in three concrete sub-periods:

I. 1945 – 1959: Reference period (prior to human interventions)

II. 1960 – 2015: Period of interventions

III. 2016 – 2023: Current conditions and management needs


The boundaries of GL-SES considered the below natural elements and associated human activities:

A. Natural elements: lagoon water body; wetland habitats and species; freshwater resources (surface, groundwater); climate.

B. Human activities: drainage efforts; water management, lagoon fishing, agriculture and associated industry, tourism.

Policy frameworks and climate change were also considered as system components. Climate change has an impact on both natural elements and human activities within the GL-SES, but cannot be changed within it. For the scope of the thesis, policy suggestions were linked to the recently revised Special Environmental Study about the Natura 2000 site of concern associated to the EU’s Birds and Habitats Directives (Skolou and Chlykas, 2021), and to associated River Basin Management Plans linked to the Water Framework Directive (WFD) (RBMP, 2013). The WFD is the principal tool for establishing a sustainable policy and management of all water resources within the EU, and requires Member States to protect and, where necessary, restore water bodies in order to reach good status, and to prevent deterioration (WFD, 2000/60).

The linkages and interconnections of components within the GL-SES, were based on the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework. DPSIR is a useful tool for analysing complex environmental problems (Gari et al., 2015), like the problem of GL salinization (Figure 1), and it has been applied on terrestrial, coastal and marine SESs (Hou et al., 2014; Patrício et al., 2016; Elliott et al., 2017; Wantzen et al., 2019; Labianca 2020; Obubu et al., 2022). The translation of SES components into management elements was based on the concept of ES, which are the benefits of nature to humans (Díaz et al., 2015; Newton et al., 2018; Maniatakou et al., 2020; Rodrigues-Filho et al., 2023). ES rely on the conditions and processes through which natural ecosystems, and the species that comprise them, sustain and fulfil human life, thus, ensuring that ecosystems achieve or maintain a healthy state is a key requirement to secure the sustainability of human activities (Sy et al., 2018; Maes et al., 2020). System Dynamics Modelling (SDM) was selected as modelling framework based on its graphical transparency, which facilitates a holistic understanding amongst stakeholders and scientists (e.g., Stave, 2010; Tiller et al., 2021; Di Lucia et al., 2021). SDM allows for the direct translation of problems into model structures as stocks and flows (Sterman, 2000; Binder et al., 2004), and is designed to improve the users understanding on the patterns of change in a system, through a process of multiple model simulations under different scenario conditions (Videira et al, 2017). Knowledge gaps about major social and ecological components where assessed by applying a variety of methods (section 2.3).
2.2 Study area

The GL-SES is located in southwestern Messinia, Greece (36°58′ N, 21°39′ E), and it is a representative example of an interlinked coastal-rural area within the Eastern Mediterranean region (Figures 2a, 2b).

2.2.1 Wetland and catchment

GL is a coastal lagoon with transitional waters which was formed around 3500 years BP (Emmanouilidis et al., 2018). GL is part of a small (approximately 40 km²) watershed – named as the Gialova Lagoon hydrological catchment (GL-HC) within this study – which contains the Xerolagados river and the Tyflomitis groundwater aquifer (Figure 2c). The main natural discharge of the groundwater aquifer (approximately 70% at Perleros and Pavlakis, 2009) is via a system of artesian springs (Tyflomitis) which was once part of GL (Bousbouras et al., 2011, Figures 2c, 2d).

For millennia the hydrology of GL was regulated by the mixing of fresh water inputs from the catchment (Xerolagados river, artesian springs of Tyflomitis) with sea water inputs from the adjacent Navarino Bay, creating a brackish environment (Emmanouilidis et al., 2018). Since the 1960s the hydrological balance of GL has been altered by extensive drainage and other misplaced human interventions, which have resulted in severe environmental changes (Lykos, 1999; Koutsoubas et al., 2000; Bousbouras et al., 2011). By the end of the last century, GL underwent progressive salinization (Koutsoubas et al., 2000; Bousbouras et al., 2011; Chatzigeorgiou et al., 2011), but previous efforts to regulate salinity within GL (increased fresh water inflows from the catchment) faced challenges already at an early stage (HOS, 2000). In fact, Bousbouras et al (2011) confirmed that the restoration actions have been abandoned in the long run, as during the period 2010-2012 only an unknown fraction from the artesian springs was estimated entering the wetland, while Xerolagados river was regularly polluted by olive-mill waste waters.
Figure 2. The GL social-ecological system (GL-SES). (a) Location of focus area in Greece. (b) Panoramic view of the focus area (picture by Paul Strehlenert). The arrows denote the place where freshwater resources entered Gialova Lagoon wetland prior to human interventions. (c) The hydrological catchment of interest (GL-HC) is delineated with a white dash; the Natura 2000 site is highlighted with blue (with light blue the buffer zone) (GR2550004, 1995; GR2550008, 2001); areas highlighted with orange are those supplied by the Tyfomimitis groundwater aquifer (RBMP, 2013); the white dots are irrigation drills for crops (olive-orchards) and the orange dots are drills for municipal water-supply (Perleros and Pavlakis, 2009). (d) Detailed view of GL-W: the lagoon area is highlighted with blue (the NW area is seasonally flooded and considered as part of the lagoon), the marshes area (S) is delineated with orange and the marshes area (N) with brown, cultivated land is depicted as green areas; light blue square dot arrows depict surface water flows to the sea, light blue lines at the marshes areas depict wetland enrichment with surface waters from Tyfomimitis artesian springs (via a gate: blue polygon). The red polygon depicts the gate that facilitates freshwater enrichment from Xerolagados river (currently not operational). Tyfomimitis artesian-springs is depicted as a light-blue area with green border. The double arrow (lagoon-sea canal) highlights the location of the channel that allows lagoon-sea water exchanges.

Today, GL has an average depth of 0.6 m and covers an area of approximately 250 ha (Dounas and Koutsoubas, 1996). However, considering that prior to human interventions GL has been part of a bigger wetland (Bousbouras et al., 2011), the delineation of the core study within this thesis has been expanded to also include the marshes and the surrounding cultivated lands. The boundaries of the core area – named as GL-W within this study – were defined at the north and east by the two man-made canals (Figure 2b, 2c, 2d). At the west, a rocky hill (also known as the Palaiokastro) and the semi-enclosed Voidokilia Bay separate the area from the Ionian Sea. A 3.8 km long and about 150 m wide natural sand formation, separates the area from the semi-enclosed Navarino Bay to the south. A sea/lagoon wide canal allows the constant water exchanges with the sea, but an inner embankment constrains the water exchanges between the lagoon and the surrounding marshes to the east (Figure 2d).
From a biodiversity point of view, GL-W is part of a wider Natura 2000 site that includes a variety of Mediterranean habitats (Chlykas and Skolou (eds), 2021, Figure 2c). The site is protected under the EU Birds and Habitats Directives as it hosts ecosystems which are of priority for conservation within the EU, and provides shelter for migratory waterbirds (EU’s Habitats Directive 92/43/EEC, 1992; GR2550004, 1995; GR2550008, 2001; EU’s Birds Directive 2009/147/EC, 2009). Historically, GL had an important fisheries value, and up to present it provides shelter to species with commercial value like the Gilt-head sea bream (*Sparus aurata*), the European bass (*Dicentrarchus labrax*), and the Flathead grey mullet (*Mugil cephalus*) (Koutsoubas et al., 2000; Zoulias et al., 2017). Apart from an important site for the local fish economy, GL-W provides a plethora of other ES to local communities and visitors (Maniatou et al., 2020). From a freshwater resources point of view, Tyflomitis groundwater aquifer is used to partly cover the water-supply needs of the local community and visitors (long-stay and tourists), while within the GL-HC many farmers choose to irrigate their orchards as a strategy to increase productivity, and avoid tree-stress during prolonged dry periods (Figure 2c, Perleros and Pavlakis, 2009). To that end, the characteristics of the local community were also considered as part of the GL-SES.

### 2.2.2 Local community and associated economy

The local community (Pylos area) has a permanent population of approximately 2500 inhabitants – comprised by the town of Pylos and the nearby villages of Gialova, Elaiofyto, Pyla, and Schinolakka – while the economy of the area has been traditionally linked to agriculture. Similar to the rest of Messinia region, after the 1970s existing crops have been gradually replaced by olives (Berg et al., 2018), and at present, within the GL-HC catchment the landscape is dominated by olive trees. The cultivation of olives is mainly based on conventional farming practices (e.g. use of herbicides and synthetic fertilizers) which result to loss of farm diversity (Myers et al., 2019), higher run-off from agriculture and subsequently environmental degradation of coastal and marine areas (Berg et al., 2018). Tourism is another source for local income. Tourism expansion goes hand in hand with infrastructure development (hotels, roads and airports), and it can provide opportunities for diversified livelihoods, but could also increase the pressures on water resources (Klein et al., 2015). At present, part of the case study is designated as an Integrated Tourist Development Area (ITDA), which is one of the biggest touristic investments in Greece, and a major driver for the economy of the area (TEMES, 2020).

### 2.2.3 Climatic conditions

The area is characterized by a Mediterranean climate, with mild wet winters and dry summers (Figure 3). The mean annual temperature is 18 °C, the mean annual evaporation is 889 mm/year (Thornthwaite method, based on Rosenberry et al., 2004), and the mean annual precipitation is 695 mm/year.

![Figure 3](image-url)

**Figure 3.** Mean monthly variations in precipitation, temperature and evaporation, based on available data (1956 – 2011), measured at the Hellenic National Meteorological Service's station of Methoni (15.6 km south of GL). MAP is for Mean Annual Precipitation, MAE is for Mean Annual Evaporation, MAT is for Mean Annual Temperature. Figure retrieved from Paper I.
2.3 Mixed methods approach

The experience from the Greek Natura 2000 sites calls for more integrated approaches in ecosystem management. To that extent, this PhD thesis has followed a mixed-methods approach integrating methodological tools from natural (e.g. field monitoring, GIS analysis) and social (e.g. consultations with stakeholders) sciences which are described below in sections 2.3.1 to 2.3.4. Table 1 provides an overview of which methodological tools were applied in each of the four papers of the thesis.

Table 1. Overview of methodological tools applied in the PhD thesis.

<table>
<thead>
<tr>
<th>Context</th>
<th>Paper I</th>
<th>Paper II</th>
<th>Paper III</th>
<th>Paper IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPSIR</td>
<td>Learning from the past; Understanding current conditions</td>
<td>Understanding current conditions; Planning for the future</td>
<td>Understanding current conditions; Planning for the future</td>
<td>Understanding current conditions; Planning for the future</td>
</tr>
<tr>
<td>Purpose</td>
<td>Drivers; Pressures; State; Impacts</td>
<td>Drivers; Pressures; State; Responses</td>
<td>State, Impacts, Responses</td>
<td>Responses; Drivers</td>
</tr>
<tr>
<td>Methods</td>
<td>Historical perspective on human-climate dynamics that have caused dramatic shifts in the functions of the GL-W.</td>
<td>Quantification of hydrological fluxes and associated lagoon salinity under current and future climatic conditions. Insights for water resources management for salinity regulation</td>
<td>Status and distribution of waterbirds in relation to wetland habitats. Links to salinization and insights for water resources management for salinity regulation</td>
<td>Co-development of suggestions for wetland restoration and management of freshwater resources, under a changing climate.</td>
</tr>
<tr>
<td></td>
<td>Participatory GIS; Conceptual schematics; Conceptual modelling (balance equations)</td>
<td>Data collection (permanent equipment, field visits); Numerical modelling (balance equations)</td>
<td>Data collections (field counts); Diversity indices</td>
<td>Participatory conceptual (CLD) and system-dynamics (SDM) modelling.</td>
</tr>
</tbody>
</table>

2.3.1 Field monitoring and observations (Paper I, Paper II, Paper III)

The focus of field monitoring and associated observations was to facilitate scientific data collection about the wetland area (uses, cover, changes), wetland water quality (salinity, but also temperature and depth variations), climatic conditions (meteorological data), and biodiversity status (waterbirds), within the GL-W (Figure 4). The aim of this approach was four-fold. First, to generate up-to-date data and improve the understanding about the natural elements of the GL-W social-ecological system (e.g., habitats). Second, to allow comparisons of salinity and waterbirds with previous studies (e.g., Arvanitidis et al., 1999; Kardakari et al., 2000; Koutsoubas et al., 2000), and identify changes and trends. Third, to provide a holistic perspective about the socio-ecological context in which these changes occurred. Fourth, to create data bases for supporting modelling and scenario analysis.

A. Land uses & Land cover (paper I)

Field observations from the period July–August 2011 (participation of the author in Bousbouras et al., 2011) and from August 2018 were used to identify the current habitat cover and land uses within and around GL-W. During field visits a portable GPS was used to mark spatial data location, while at a second stage the observations were digitized and analyzed using computer GIS software ArcGIS (Version 10.5). These observations were used in remote sensing and GIS analysis to facilitate analysis about wetland changes overtime and current status (section 2.3.2).
Figure 4. Map with monitoring stations and bird count points within GL-W. The pink dots highlight the stations used in Paper II, while the green circles depict the station used in Paper IV (provided by the Gialova Project, 2023). Detailed symbology is provided under figure 2d.

B. Hydrology & Water quality (paper II)

Data collection for the quantification of hydrological conditions and associated salinization was based on the installation of permanent equipment and seasonal field campaigns. The monitoring set-up consisted of one meteorological station, and several stations equipped with CTD-10 sensors for monitoring water conductivity (converted to salinity), temperature and depth within GL-W (Figure 4).

Meteorological measurements were conducted with a Decagon Devices, Inc. system, including a relative humidity and air temperature sensor (VP4), a 2-D sonic anemometer (DS-2), a solar radiation sensor (pyranometer), and a rain gauge (ECRN-100), all installed in March 2016. Data were recorded using EM-50 loggers. Meteorological data were collected with a sampling interval of 5 min and averaged (or accumulated for rainfall and solar radiation) over a day. Gaps in the meteorological data record were filled using time series from two other meteorological stations – one located in an olive orchard 5 km from the Gialova lagoon, the other located at Methoni (data obtained from the National Observatory of Athens).

For this study, conductivity was estimated from the average value of the two central sensors, considered as representative for the whole lagoon. Missing data from late 2017 and January 2018 were gap-filled using the time series from the northern measurement site, which were well-correlated with that from the central measurement site. Conductivity values (expressed in mS cm$^{-1}$) were converted to salt concentrations (g/ L) using the empirical relation, $C_{S} = 0.4665 \times EC^{1.0878}$, where EC is the electrical conductivity at 25 °C (Williams, 1986). Water depth variations were obtained from the northern sensor, which had no missing values and had remained at the same vertical position throughout the duration of the monitoring. Meteorological data, and water salinity, temperature, and depth data for years 2016-2017 are stored in Bolin Centre Database (2023a).

C. Biodiversity status (paper III)

The status and distribution of waterbirds was assessed as a proxy to understand the effect of wetland salinization on biodiversity, but also as an indicator for biodiversity status of the Natura 2000 site. Since the wetland is protected under the EUs Birds directive (GR2550008, 2001), future managers should consider conservation needs for achieving favorable conditions for waterbirds. However, the available knowledge on the current status and distribution is limited to data from older reports (Standard Data Forms for site GR2550008 based on Kardakari, 2000), which have been quite detailed, but outdated.
In this study, monthly field visits were conducted during the period October 2016 to January 2019, with the aim to complement existing information about the site, evaluate the current status and distribution of waterbirds in the GL-W, and allow comparisons with previous studies (e.g., Kardakari, 2000). Data collection was based on bird counts following a methodology with predetermined observation points (Bousbouras et al., 2011). The protocol consisted of 13 points covering all the sub-areas of the wetland (Figure 4). The field equipment consisted of binoculars (10x magnification), a scope (20-60x85) and a digital camera, while Collins birds guide (Svensson et al., 2010) was used for birds’ identification.

During the censuses, all waterbirds (seen and heard) were recorded, i.e., a complete census (Gregory et al., 2004), and they were listed according to BirdLife taxonomic basis (BirdLife International, 2019). Data interpretation was based on the calculation of waterbirds diversity indices, namely species richness (S), species abundance (N), relative abundance (RN), and Shannon-Weiner Index (H), an approach which is commonly used in birds’ studies (e.g. Issa, 2019; Bibi and Ali, 2013). The temporal distribution of waterbirds was estimated at a season (wet, dry) and period level (wintering, spring/autumn migration, breeding) based on species richness and abundance. To assess the spatial distribution of waterbirds per season and per period, the indices (RN) and (H) were used.

The count data were analysed with generalized linear models assuming Poisson or Negative Binomial (for overdispersed data) distribution of the dependent variable, using a log link function, as suggested for count data analysis (Seavy et al., 2002; O’Hara and Kotze, 2010; Warton et al., 2016). Statistically significant differences for indices (S), (N), and (RN) were based on pairwise comparisons of the Estimated Marginal Means produced by the generalized linear models, applying the Bonferroni adjustment for multiple comparisons. For comparing the Shannon diversity indices, the Hutcheson t-test was applied (Hutcheson, 1970). The statistical significance was set at \( \alpha \leq 0.05 \). The processing of the results was conducted in Microsoft Excel, and the statistical analysis in IBM SPSS Statistics Data Editor. The primary dataset (waterbirds monthly observations) is archived in the Bolin Centre Database (2023b).

2.3.2 GIS analyses (Paper I)

To understand the causal links between human activities and dynamics within GL-SES, an integral step of the PhD thesis was to investigate how past interventions have affected the hydrology and associated functions of the wetland during the period 1945 – 2015. A set of aerial photographs, covering the period of interventions from 1945 to 2010 (Google Maps image from 2010), and associated conceptual schematics were used to reconstruct the hydrological conditions over time and to interpret and visualize the prevailing hydrological conditions in the different time periods (Figure 5).

Figure 5. An example of coupled conceptual schematics and aerial photographs approach, used in Paper I. P is for precipitation and E for Evaporation.
To compare land cover and uses between reference (prior to interventions) and present conditions, two maps were constructed based on spatial data interpretations and field observations (section 2.3.1). The basic layer of the reference map was the digitized 1945 aerial photograph, and the basic layer of the present map was a digitized high-resolution satellite image from 2010 available on the Google Earth platform. Participatory Geographical Information System (PGIS) facilitated local data collection and visualization on paper (section 2.3.3), and the information was then digitized and analyzed using computer GIS software ArcGIS (Version 10.5).

2.3.3 Consultation with stakeholders (Paper I, Paper IV)

Co-management relies on the collaboration of a diverse set of stakeholders (Carlsson and Berkes, 2005; Folke et al., 2005), to enhance co-production and dissemination of knowledge, and integration of scientific and local knowledge in decision making (Kofinas, 2009). For the scope of this PhD, participatory approaches have been based on semi-constructed interviews and group discussions.

A. Interviews with key informants (paper I)

For the scope of the review study (Paper I), the engagement of stakeholders was based on PGIS. In essence, PGIS is a tool for gathering data through interviews and questions by using paper maps to record spatial details (Morrow, 1999 in De Souza and Clark, 2018). The study engaged five local elderlies from the area who were considered key informants, as they had access to local knowledge. To ensure that the information gathered from these interviews was robust, only answers that were consistent among the key informants were considered. The aim of PGIS was twofold. First to get a better understanding about traditional practices and relationships of local communities with natural resources (e.g., fishing). Second to complement our understanding about types of crops and vegetation within and around the wetland prior to human interventions (1960s). In practice, PGIS facilitated local data collection and visualization on paper, and the information was then digitized and analyzed using software ArcGIS (section 2.3.2).

B. Group discussions (Paper IV)

Paper IV was built around iterative consultation processes which lasted for four years, and involved around 100 stakeholders (SHs) in six sectoral and three Multi-Actor Laboratory (MAL) workshops (Table 2). The aim was to provide a platform for a dialogue about local needs and concerns, to investigate the application of participatory modelling in building a common understanding among the different groups of SHs, and to integrate local and scientific knowledge in a decision-making tool suitable for exploring alternatives for wetland restoration and management of associated freshwater resources (section 2.3.4).

The purpose of the sectoral workshops was to bring together local experts to describe the characteristics of the system from their perspective. During the sectoral workshops, the identified key elements and their connections, as long as challenges and opportunities for improved land-sea interactions and cross-sectoral collaborations (Tiller et al., 2021). These discussions formed the basis for the conceptualization of social and ecological system characteristics into six separate mind-maps which were later condensed into a unified mind-map at a case study level, and transformed into a Conceptual Model by adding signs to denote the nature of interaction between two variables similar to a Causal Loop Diagram (GL-CLD), which is a common tool for system analysis (Morecroft, 1982; Lane, 2008). The purpose of the MAL workshops was to bring representatives from each sector to further facilitate discussions, validate the outcomes of previous workshops and the development of an SDM, but also to co-create suggestions for the sustainable development of the area. The identification of stakeholders was based on major economic activities and characteristics of the GL-SES. Thus, the SHs were representatives from the agriculture, olive-oil manufacturing, coastal fishing and tourism sectors, as well as government administrative and legislative bodies and expert groups (scientists, NGOs). The latter identified as regulators and influencers of policy making (Newton and Elliott, 2016). The selection of associated stakeholders for each sector has followed the snowball method, as described in Tiller et al. (2021).
Table 2. Structure, participation, purpose and number of participants during consultation processes under Paper IV.

<table>
<thead>
<tr>
<th>Workshop linked to</th>
<th>Participants linked to</th>
<th>Purpose</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Olive-oil producers and agronomists</td>
<td>Mind mapping of different perceptions with regards to land-sea interactions</td>
<td>16</td>
</tr>
<tr>
<td>Local Industry</td>
<td>Olive-mills and pomace-mills</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Fishing</td>
<td>Fishing, both in transitional and coastal waters</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Tourism</td>
<td>Hotels, local enterprises (restaurants, gift shops), outdoor activities</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Administration/ local authorities</td>
<td>Municipality, regional government, water management, forestry, archaeology</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Institutions/NGOs</td>
<td>Universities and foundations with on-going research within the area, NGOs for nature conservation</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>MAL 1</td>
<td>representatives from all sectors</td>
<td>CLD validation (structure &amp; connections)</td>
<td>22</td>
</tr>
<tr>
<td>MAL 2</td>
<td>representatives from all sectors</td>
<td>SDM validation (structure and behaviour)</td>
<td>19</td>
</tr>
<tr>
<td>MAL 3</td>
<td>representatives from all sectors</td>
<td>Scenarios</td>
<td>25</td>
</tr>
</tbody>
</table>

2.3.4 Modelling and scenarios (Paper I, Paper II, Paper IV)

A. Numerical modelling

To study the consequences of changing hydrologic regimes on wetlands (in terms of water quantity and quality), it is necessary to quantify hydrologic fluxes. However, this is generally difficult due to the complex fresh-lagoon-sea water interactions in wetlands, especially in the absence of direct flow measurements. The lack of monitoring data for water exchanges made the prediction of hydrologic changes challenging, and required indirect approaches that leverage the limited available data.

In this PhD, a minimal coupled water–salt mass balance model was developed to describe both freshwater and saline flux exchanges of coastal water bodies, and associated lagoon salinization. Overarching mass balance considerations and closure over a whole lake or wetland system have been used in other studies to constrain unknown fluxes of water, solutes and latent heat (Jarsjo and Destouni, 2004; Destouni et al., 2010). Previous examples have also demonstrated the advantage of this approach for coastal lagoons (Martinez-Alvarez et al., 2011; Rodellas et al., 2018). The unknown hydrologic fluxes within the GL-W were estimated following a mass balance approach based on equations:

\[
dh/dt = P - E + Q_{\text{fresh}} + Q_{\text{salt}} \quad (Eq. 1)
\]

\[
d(C_S h)/dt = \begin{cases} C_G Q_{\text{salt}}, & Q_{\text{salt}} < 0 \\ C_S Q_{\text{salt}}, & Q_{\text{salt}} > 0 \end{cases} \quad (Eq. 2)
\]

where \( h \) is the water depth in the lagoon, \( P \) and \( E \) are the rates of precipitation into and evaporation from the lagoon respectively, \( Q_{\text{fresh}} \) and \( Q_{\text{salt}} \) are the exchange rates of lateral freshwater and saline water fluxes into and from the lagoon (volumetric flow rates normalized by the lagoon area \( A \)), \( C_G \) is the salt concentration within GL-W and \( C_S \) is sea salinity assumed constant at 38.5 g/ L (based on Civitarese et al., 2013).

In Paper I, equations (1) and (2) were modified to allow a conceptual comparison between reference (prior to 1960s) and present conditions. In Paper II, equations (1) and (2) were used to quantify current hydrological fluxes and estimate future changes due to climate warming and reduced precipitation. Specifically, field data (section 2.3.1) and model-based evaporation rates were used to constrain equations (1) and (2) and determine \( Q_{\text{fresh}} \) and \( Q_{\text{salt}} \), which were the unknown rates in these equations. Precipitation rate and water depth were measured, while evaporation was estimated using the Penman equation, parameterized with local meteorological data. In equation (2), \( Q_{\text{salt}} \) was the only unknown, whereas salt mass was obtained as the product of salt concentration \( (C_G) \), measured, and water depth \( (h) \) within GL-W.
With this information, $Q_{salt}$ was obtained from equation (2), and used in equation (1) to finally derive $Q_{fresh}$.

**B. Systems Dynamic modeling**

System Dynamics (Sterman, 2000) was selected as modelling framework, based on the graphical transparency of this type of modelling which facilitates a holistic understanding amongst stakeholders and scientists. The clarity and transparency of the approach enables iterative testing of the models hence making these models particularly useful for interactive use by and with stakeholders (Videira et al., 2017; Viaene and de Kok, 2020; de Kok and Viaene, 2021). The process aims at providing an understanding of the system in question and providing possible policy solutions to help solve the problem in question, whilst accounting for externalities and trade-offs. In this respect SDM approaches pair well with qualitative research methodologies and participatory processes, focusing on understanding the whys and the hows of a particular problem (Guest et al, 2013), under a multitude of perspectives. To that end, the application of a participatory modeling approach in decision making could elucidate the major constrains and possible trade-offs at an early stage, but also provide tools for the co-development of scenarios and strategies together with the stakeholders (Smetschka, and Gaube, 2020).

The scope of the SDM for the case of Gialova Lagoon (GL-SDM) was to explore water management alternatives for the regulation of salinity within the wetland, in relation to associated freshwater (surface and groundwater) availability at a catchment level, under different climatic and local development scenarios (see below). The architecture of the GL-SDM was based on the structure of the GL-CLD that was developed during group discussions (section 2.3.3). The development of the SDM was performed in Vensim PLP software, and it required a series of steps from defining the stock-flow architecture, to collecting quantitative data for parameter setting, formulating equations, model calibration and model validation (Viaene and de Kok, 2020; de Kok and Viaene, 2021).

The GL-SDM has an annual calculation step. The simulations cover the period 1976-2100, which is divided in two distinct periods; the reference period which is from 1976 to 2025, and the scenario period which is from 2026 to 2100. The scenario period is further divided into a short- (2026-2050), mid- (2051-2075) and long-term (2076-2100) period. The quantification of the model was based on local knowledge and available data and insights from previously published research (Koutsoubas et al., 2000; Perleros and Pavlakis, 2009; Bousbouras et al., 2011; Paper I; Paper II; Paper III; Bray et al., 2022), as well as on on-going monitoring projects (Gialova Project, 2023). The quality of the model was improved by engaging SHs in the process of model confidence building (Forrester and Senge, 1980), obtaining feedback on the model scope (boundaries and level of detail), model structure (SES components included in the model), the model dynamics (time-dependent patterns generated with the models) and the policy implications and relevance for decision making (Table 2).

Even though the GL-SDM was primarily developed to provide simulations at an annual time-step, it was possible to add seasonality and create look-ups which depict the monthly salinity variations based on collected data from previous (Paper II) and on-going monitoring activities (Gialova Project, 2023). In both water bodies, the variation of salinity follows similar trends with salinity at the marshes ranging between more extended min and max monthly margins (Gialova Project, 2023). The available data were inserted in the GL-SDM to allow simulations of monthly salinity values at lagoon and marshes scale.

**C. Scenarios**

The development and analysis of scenarios is increasingly used to support strategic planning and decision-making in complex social-ecological systems, by providing a platform to think through the implications of alternative options in the face of uncertain future developments (Zurek and Henrichs, 2007). Since social-ecological systems are considered complex adaptive systems, comprising a social, human-made, and a natural dimension (Westley et al., 2002), a scenario analysis could be applied to
allow for voicing conflicting opinions and worldviews in a structured manner (Zurek and Henrichs, 2007). For the scope of the thesis, by the term scenario it refers to a plausible and often simplified, though imaginative, description of the future of the GL-SES based on a coherent and internally consistent set of assumptions about key driving forces and relationships (Zurek and Henrichs, 2007).

In Paper II, climatic scenarios were combined with altered water resource management scenarios, to assess the effects of changing climatic conditions and wetland restoration alternatives on GL salinity, and provide insights for future water management (Table 3). The long-term climatic averages were based on available data (section 2.2.3), while climate change components were based on results of a regional climate model forced by global climatic conditions under high CO₂ emissions (denoted as A2), with predictions extending to the year 2100 (Gao and Giorgi, 2008). In essence, Emission Scenario A2 is close to the Representative Concentration Pathway (RCP) 8.5 (van Vuuren et al., 2011). The climatic scenarios were combined with altered water resource management scenarios in which the lateral freshwater fluxes were either reduced due to intensified water use or increased by attempts to restore the Gialova lagoon to its original state of a brackish wetland. To consider a wide range of possible management outcomes, the study considered freshwater flux changes varying continuously from a 50% reduction to a 50% increase with respect to the current conditions.

In Paper IV, the hydroclimatic components (long-term averages and the associated RCPs 2.6, 4.5 and 8.5) which were used as inputs in the GL-SDM, were extracted from downscaled climate models for the selected area with a spatial analysis of 10 km x 10 km. The data were acquired by the Research Centre for Atmospheric Physics and Climatology of the Academy of Athens and were further processed in Microsoft Excel software (Table 3). Although the GL-SDM was developed in a way to simulate all three RCPs, to compliment the understanding from Paper II, Paper IV provided simulations under the influence of RCP 4.5, in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter (Van Vuuren et al., 2011). The scenarios were developed around SHs’ suggestions (section 2.3.3) considering a variety of water-related societal and ecological needs, with the aim to explore wetland restoration alternatives for the regulation of GL salinity and the enhancement of associated ES, under different local development scenarios and associated pressures on freshwater availability (surface and groundwater/ artesian; Table 3).

Table 3. Overview of key variables considered for the description of current conditions and future scenarios in Papers II and IV.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>paper IV</th>
<th>paper II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climatic conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPCC</td>
<td>(RCP) 4.5</td>
<td>(EmS) A2</td>
</tr>
<tr>
<td>wetland</td>
<td>P: 710 mm/year</td>
<td>P: 695 mm/year</td>
</tr>
<tr>
<td>E: 900 mm/year</td>
<td>P: ↘ by 2 %</td>
<td>E: ↘ by 11 %</td>
</tr>
<tr>
<td></td>
<td>E: ↗ by 9%</td>
<td>E: ↗ by 12%</td>
</tr>
<tr>
<td>catchment</td>
<td>P: 908 mm/year</td>
<td>P: ↘ by 10 %</td>
</tr>
<tr>
<td>PET: 837 mm/year</td>
<td>E: ↗ by 14%</td>
<td>E: ↗ by 12%</td>
</tr>
<tr>
<td></td>
<td>P: ↘ by 11 %</td>
<td>PET: ↗ by 13%</td>
</tr>
<tr>
<td></td>
<td>E: ↗ by 12%</td>
<td>PET: ↗ by 15%</td>
</tr>
<tr>
<td></td>
<td>CC effect on GW recharge (as part of wetland scenarios)</td>
<td></td>
</tr>
<tr>
<td><strong>Restoration of connectivity with natural flows and between habitats</strong></td>
<td>artemis-marshes connectivity</td>
<td>Changes in flux inputs from the artesians springs (+/- 50 %) compared to current conditions</td>
</tr>
<tr>
<td></td>
<td>river-marshes connectivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lagoon-marshes connectivity</td>
<td></td>
</tr>
<tr>
<td><strong>Freshwater management</strong></td>
<td>Irrigation</td>
<td>Variations in groundwater abstractions were considered as part of changes in freshwater fluxes under wetland restoration scenarios</td>
</tr>
<tr>
<td></td>
<td>olive irrigation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>irrigation index</td>
<td></td>
</tr>
<tr>
<td></td>
<td>network losses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>per capita water-demand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>per bed water-demand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>long-stay visitors by 2100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>beds' availability by 2100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pollution control</td>
<td>not considered</td>
</tr>
</tbody>
</table>

Abbreviations: IPCC is for Intergovernmental Panel for Climate Change, RCP is for Representative Concentration Pathway, EmS is for Emission Scenarios, P is for Precipitation, E is for Evaporation, PET is for Potential Evapotranspiration, CC is for Climate Change, GW is for Groundwater resources.
3 Results

3.1 Scientific knowledge

3.1.1 Wetland salinization and associated hydrological fluxes

Based on results from Paper I, the combined effects of freshwater diversion and climate have led to increased salinity in the wetland over time (Figure 6). From a climate point of view, the analysis of the long-term climatic data showed that on an annual basis, a seasonal water deficit developed during the summer and into the autumn resulted in a net water deficit of approximately 200 mm/year. From an intervention point of view, the restoration of wetland connectivity with the sea (opening of the sea/lagoon canal in 1976), under the absence of any surface freshwater inputs, led to increasingly saline conditions in the wetland over the years as the annual freshwater deficit was met primarily by seawater inputs. The partial restoration of freshwater inflows in 1998–1999 led to wetland de-salinization. However, the efforts for water regulation were abandoned a few years later, and up to present day only an unknown fraction from the artesian springs flow enters the marshes and lagoon.

![Figure 6](image) Annual water balance (mm/year) during the study period and major human interventions affecting the wetland hydrological balance. Interventions leading to wetland degradation are highlighted with red border. Interventions aiming to wetland restoration (connectivity with fresh and sea water bodies) are highlighted with blue border.

In the absence of direct flow measurements, the water balance approach provided estimates of the major hydrologic fluxes exchanged through the GL, allowing the assessment of its overall water balance over the 2-year study period (Paper II). As it is shown in Figure 7a, under measured climatic conditions (2016-2018), about 40% of the annual freshwater inputs into the lagoon were from precipitation, and 60% from lateral freshwater flows, namely groundwater exchanges, and surface water inputs (partial flow from artesian springs). Approximately 70% of the outputs were due to evaporation, with the remaining 30% being water flow from the lagoon to the sea. Based on collected data from the permanent equipment, the study has shown that under those climatic conditions and flows, the lagoon mean annual salinity (MAS) was at 34.4 g/L (measured from March 2016 to December 2017) with a monthly variation between 19.1 and 49.3 g/L (Figure 7b). On an annual basis, the lagoon was under hypersaline conditions (above sea salinity) for at least 30% of the year. Salinity in the lagoon is expected to increase even more, unless freshwater inputs are enhanced by restoring hydrologic connectivity between the lagoon and the surrounding freshwater bodies (Paper II). In fact, recent monitoring (2021-2022) revealed that the MAS within the lagoon has increased to 39.7 g/L, while the time under hypersaline conditions to almost 50% of the year (Paper IV).
To adapt to expected climatic conditions by the end of 2100, and maintain the current annual average salinity in the lagoon, a more than 50% increase in freshwater inputs should be achieved, and the natural discharge from Tyflomitis artesian springs could fulfil that demand (Paper II). However, future water availability from the springs is expected to be less due to increased groundwater abstractions (irrigation, municipal water supply) and decreased groundwater recharge (climate change). Thus, under future conditions, managing artesian freshwater inputs to maintain current salinity levels appears to be challenging, and there will be a need for additional freshwater inputs (e.g. Xerolagados river).

### 3.1.2 Wetland biodiversity: Habitats and waterbirds

#### A. Habitats

According to results from Paper I, prior to human interventions, GL was a continuum of ecosystems comprised of open water (lagoon), and marshlands including the artesian springs of Tyflomitis, but at present it is a fragmented ecosystem with restricted water exchanges (Figure 8). Due to man-made constructions, the size of wetland habitats was reduced by 7.5% (from 458.3 to 412.3 ha), as part of the wetland was drained and converted to agricultural land. Overall, the vegetation cover within the wetland area was reduced by 46.7% (from 193.7 to 103.2 ha), while due to salinization, the brackish species (*Typha* spp., *Phragmites australis*) in the remaining marshes were mainly outcompeted by halophytic species (*Salicornia europaea* and *Juncus* spp.). Part of the wetland vegetation was covered by water, increasing the open water coverage within the wetland by 22.8% (from 250.8 to 307.9 ha), but the main lagoon was restricted to about 250 ha (including the area at the northwest side which is flooded during the wet period), as an inner embankment separated the lagoon from the additional open water area (Paper I).
B. Waterbirds

The wintering population of several wildfowl species (except *Anas platyrhynchos*), herons, and the coot, as well as migrating populations of waders have declined over the last 20 years (*Paper III*), a change which has been associated to the loss of wetland ecosystems and their transformation from fresh/brackish to saline habitats, due to salinization (*Paper I, Paper III*). Nevertheless, the wetland continues to be an important site for birds and especially for waterbirds (*Paper III*). The regular observations during the period 2016 – 2018 have shown that under current conditions the area provides shelter to at least 149 bird species representing 43 families and 15 orders. Among these, 36 species were identified as threatened at an International, European or/and national level, and 40 species were listed in the Annex I of the EU’s Birds Directive. Almost 60% of the recorded species (81 species) were identified as wetland dependent species, of which 66 species were identified as waterbirds (7 orders, 11 families). The wetland is mostly used by ducks, coots, herons, waders, flamingos and cormorants (*Paper III*). All parts of the wetland supported waterbirds and threatened species, but their occupation by waterbirds varied between seasons and periods (Table 4).

Table 4. Distribution of waterbirds at the sub-areas of the wetland. The areas are illustrated in Figure 2d.

<table>
<thead>
<tr>
<th>Sub-areas</th>
<th>Size (ha)</th>
<th>Habitat characteristics</th>
<th>Waterbirds</th>
<th>Presence</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagoon (open water)</td>
<td>225.5</td>
<td>Area covered by open water with an average depth of 0.6 m. Salt meadows at the fringes of the lagoon, and old embankments (creating parallel islands) covered by halophytes at the northeast side.</td>
<td>Wildfowl</td>
<td>Nov – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coots</td>
<td>Nov – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Waders</td>
<td>May – Oct</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Herons</td>
<td>All year</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cormorants</td>
<td>Nov – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flamingos</td>
<td>Aug – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gulls</td>
<td>All year</td>
<td>F, R, N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Grebes</td>
<td>Nov – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td>Lagoon (NW area)</td>
<td>22.8</td>
<td>Mixed habitat mainly covered by shallow ponds (flooded during the wet period), and soil areas with limited vegetation.</td>
<td>Waders</td>
<td>All year</td>
<td>F, R, N</td>
</tr>
<tr>
<td>Marshes (S)</td>
<td>94.6</td>
<td>Mixed habitat covered mainly by shallow open waters, salt meadows and old embankments (creating parallel islands) covered by halophytes. Small parts are covered by reeds.</td>
<td>Wildfowl</td>
<td>All year</td>
<td>F, R, N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coots</td>
<td>Aug – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Waders</td>
<td>Feb – Oct</td>
<td>F, R, N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Herons</td>
<td>All year</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cormorants</td>
<td>Nov – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flamingos</td>
<td>Aug – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gulls</td>
<td>All year</td>
<td>F, R, N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rails &amp; Crakes</td>
<td>Aug – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td>Marshes (N)</td>
<td>44.4</td>
<td>Salt meadows, which neighbor cultivations at the north, separated by relative deep drainage channels (max depth ≥ 1.4 m)</td>
<td>Swans</td>
<td>All year</td>
<td>F, R, N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rails &amp; Crakes</td>
<td>Aug – Apr</td>
<td>F, R</td>
</tr>
<tr>
<td>Cultivations (C)</td>
<td>110.7</td>
<td>Managed areas mainly covered by olive trees (23%) horticulture and grain crops (36%).</td>
<td>Herons</td>
<td>Nov – Jul</td>
<td>F, R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gulls</td>
<td>Feb – Jul</td>
<td>F, R</td>
</tr>
</tbody>
</table>

Abbreviations: F is for feeding area, R is for resting area, N is for nesting area.

3.2 Local knowledge and needs

3.2.1 Fish species

According to the local fishermen, GL serves as a breeding ground for young fish which enter the lagoon in March, with the help of tidal currents through the sea-lagoon canal, remain for several months, and then migrate back to the open sea from June onwards (*Paper IV*). Prior to human interventions, fish CPUE (catch per unit effort) has been around 60 kg/ha, and it was based on the fishing of eels (*Anguilliformes* spp.), sea bream, sea bass and grey mullet (5th sectoral workshop). In the past, eel CPUE has been up to approximately 14 kg/ha, but under present conditions, the fishermen rely mainly on the populations of sea bream, sea bass and grey mullet, and they reported a mean annual fish CPUE almost 30% lower compared to the past (normalized to exclude eels), at around 32 kg/ha (3rd sectoral workshop).
The lower fish CPUE was associated with lagoon salinization, and they highlighted that when lagoon salinity exceeds sea-salinity level (over 38.5 g/L), fish need to consume more energy to regulate the salt content inside their bodies (osmosis), which gradually weakens their health status. They also added that when lagoon salinity levels become higher than fish tolerance levels, there is a high risk of extended fish death which could have an impact on fish CPUE, but also on area recognition in the extreme case of a collapse (Figure 9). On the other hand, they indicated that if salinity fluctuations could be regulated to fish optimum levels (20 - 40 g/L), fish CPUE could be increased up to approximately 42 kg/ha.

3.2.2 Wetland restoration and associated freshwater resources

Lagoon salinization was linked to past human interventions and increased inland abstractions for irrigation and water supply (Paper IV). The SHs were aware that Xerolagados river and Tyflomitis artesian springs were once connected to GL-W, and that these resources could be used for improving salinity conditions within the wetland (1st MAL workshop). However, they identified several challenges towards that direction. A tentative enrichment from Xerolagados river could create more problems, as the river is regularly polluted by olive-mill wastewaters (2nd and 3rd sectoral workshops). In addition, Xerolagados was described as a river with a flow during the wet period (Nov. – Apr.), and thus, to use these resources during the critical summer period there will be a need to invest in water storage infrastructure. The water from Tyflomitis artesian springs was mentioned as a more “secure” source, but as the groundwater resources from Tyflomitis are increasingly used for domestic use and irrigation, the available water volumes may not be enough for wetland de-salinization (2nd MAL workshop).

The participating olive-oil producers (1st sectoral workshop), mentioned that the majority of local farmers perceive the area as being “rich” in groundwater resources, and thus they tend to irrigate their farms without considering a possible groundwater scarcity. They estimated that on-going groundwater abstractions for irrigation were at levels close to 5,300 m³/hectare (annual mean), which is almost double from what they considered as “tree needs”. They also mentioned that irrigation demand is expected to increase in the coming years due to climate change, which could add pressure on the groundwater resources. In addition to abstractions for irrigation, Tyflomitis groundwater resources were reported as important for supporting the water demand of the local population and tourism, and according to the local water management plan, the municipality has the capacity to abstract up to 525,000 m³/year (5th sectoral workshop).
3.2.3 Environmental management of GL Natura 2000 site

The lack of proper environmental management, was mentioned by most SHs as an insurmountable obstacle towards wetland restoration (1st MAL workshop). The designation of the area as a Natura 2000 site, almost twenty years ago, was not supported by the establishment of a management body (MB), which created an institutional gap (5th sectoral workshop; Paper I). According to public administration SHs, decision-making has been exhausting, and often ‘trapped’ by bureaucracy, as the involved administration units have been often faced with different laws, which sometimes compete with each other. Consequently, complicated issues like managing freshwater resources for wetland restoration, cannot be properly addressed and often lead to conflicts. In addition, the SHs highlighted the lack of “cooperation culture”, and they mentioned that the workshop gave them the opportunity to sit around the table and discuss about common issues in a constructive way for the first time (5th sectoral workshop).

3.3 Integrating scientific and local knowledge for wetland restoration

3.3.1 Participatory modelling

The process of co-developing a CLD together with local SHs provided a platform for promoting a common understanding among research and community parties, and complemented existing research understanding with local insights and expertise (Paper IV). In essence, the co-developed GL-CLD provided a tool for combining the above reported scientific knowledge and local needs/concerns (sections 3.1 and 3.2) into a conceptual model which was easily understood by the participants, while at the same time had enough complexity to integrate a variety of social-ecological components (Figure 10).

---

**Figure 10.** (a) GL-CLD for wetland restoration and management of associated freshwater resources under a changing climate. Variables highlighted with *italics* depict ES of relevance to this thesis (e.g. food supply). (b) Color explanation: variables associated to freshwater bodies and flows are highlighted with *light blue*, wetland water bodies are highlighted with *teal*. Variables associated to irrigation are highlighted with *green*, local population and tourism are highlighted with *orange*. Suggestions for wetland restoration are highlighted with *blue*, while suggestions for management of freshwater resources are highlighted with *brown* (these variables are connected with dotted lines to depict that they are not yet implemented). (c) Explanation of arrows and signs (plus or minus): If an arrow from variable A to B has a plus sign, then a change in variable A will lead to a change in the same direction in variable B. For example, an increase in groundwater quantity causes an increase groundwater availability. If the arrow has a minus sign, a change in variable B will lead to a change in the opposite direction for variable A, such as an increase in evapotranspiration causes a decrease in natural discharge. Figure from Paper IV.
Further to the co-development of the GL-CLD, the SHs were asked to envisage and discuss about desired futures, and subsequently try to agree on a common vision about the area (1st MAL workshop). Their shared vision was summarized as: “Join forces in creating the Brand Name of Sustainable Messinia that expands across all sectors, activities and products”, highlighting that sustainable water resources management is the key element for ensuring societal well-being and ecological functions (Paper IV).

3.3.2 Exploring alternatives for lagoon de-salinization

To address local concerns and provide suggestions for sustainable management of water resources within the GL-SES, the GL-CLD was quantified into a Systems-Dynamic model (GL-SDM), which was used to simulate what-if scenarios. According to SHs, wetland restoration should be among the first priorities towards achieving sustainability, while they suggested a number of alternatives (e.g. smart irrigation) which could foster the sustainable use of freshwater resources (surface and groundwater) and increase resilience against climate change (Table 5). These suggestions were inserted to the GL-CLD as issues of concern and generated feedback loops within the system (Figure 10).

<table>
<thead>
<tr>
<th>Water body</th>
<th>Aim of intervention</th>
<th>Model inputs</th>
<th>Simulations</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland</td>
<td>Restoration of connectivity with natural flows and between habitats</td>
<td>artesian-marshes ($I_{spring}$)</td>
<td>varying from: ≈ 30 to 100</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>river-marshes ($I_{river}$)</td>
<td>varying from: ≈ 7 to 40</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lagoon-marshes ($I_{habitat}$)</td>
<td>varying from: ≈ 40 to 90</td>
<td>%</td>
</tr>
<tr>
<td>Freshwater</td>
<td>Irrigation</td>
<td>olive irrigation</td>
<td>varying from: ≈ 5,300 to 2,800</td>
<td>m²/hectare</td>
</tr>
<tr>
<td></td>
<td></td>
<td>irrigation index</td>
<td>varying from: ≈ 0.76 to 1.43</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Water-supply</td>
<td>network losses</td>
<td>varying from: ≈ 30 to 15</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>per capita demand</td>
<td>varying from: ≈ 90 to 80</td>
<td>m³/person</td>
</tr>
<tr>
<td></td>
<td></td>
<td>per bed demand</td>
<td>varying from: ≈ 150 to 135</td>
<td>m³/bed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long-stay visitors by 2100</td>
<td>varying from: ≈ 420 to 530</td>
<td>people/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>beds' availability by 2100</td>
<td>varying from: ≈ 2400 to 2700</td>
<td>beds/year</td>
</tr>
<tr>
<td>River pollution</td>
<td>pollution control</td>
<td>varying from: NO to YES</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: $I_{spring}$ is an index that depicts the level of connectivity between Tyflomitis artesian springs and the marshes, $I_{river}$ is an index that depicts the level of connectivity between the Xerolagados river and the marshes, $I_{habitat}$ is an index that depicts the level of connectivity between the lagoon and the marshes.

In theory, the problem of GL salinization is a matter of water quantity, and it could be ‘solved’ by restoring the hydrologic connectivity between the lagoon and the surrounding water bodies. As it is shown in Figure 11, under current groundwater abstractions rates and projected climatic conditions (RCP 4.5), the re-establishment of wetland connectivity with the Tyflomitis artesian springs (at 100%) in parallel with the restoration of habitat connectivity within the wetland (at 90%), could drop mean annual lagoon salinity to levels close to 33 g/L by 2050, and remain to these levels until 2060, but in the long run, salinity is expected to increase up to 42g/L by 2100. To achieve the target of lagoon de-salinization to a mean annual value around 30g/L by 2035 (10-year restoration plan), there will be a need for additional freshwater inputs from Xerolagados river, but to that end there is a need to stop river pollution.
Figure 11. GL-SDM simulations for lagoon de-salinization under different scenarios, based on outcomes from Paper IV. The description of the selected scenarios is given within the figure as embedded table (under the grey area). Model simulations about the time (fraction of the year) under hypersaline conditions (mean annual time during the selected period) are also presented in the table (under the blue area). All scenarios assume an implementation period of 10-years starting in 2026. I\textsubscript{artesian} is an index that depicts the level of connectivity between Tyflomitis artesian springs and the marshes, I\textsubscript{river} is an index that depicts the level of connectivity between the Xerolagados river and the marshes, I\textsubscript{habitat} is an index that depicts the level of connectivity between the lagoon and the marshes. Tentatively, the water inputs from Tyflomitis springs could lead to lagoon de-salinization even without freshwater inputs from Xerolagados (Paper IV), but this would imply coordinated efforts for reducing groundwater abstractions from Tyflomitis aquifer by 2035 (Figure 11). According to stakeholders, among others, such efforts should aim to improve the water-supply network, to reduce daily water consumption, to follow a tourism development model that will result to a low Tourism Intensity Rate by 2100 (less than 100 beds per 100 citizens, according to S0eS, 2017), and to adopt water-saving irrigation practices (Table 5). If such mitigation efforts could be adopted, the model suggests that salinity could be regulated around 30 g/L by 2050, and be maintained to these levels by 2100. The period under hypersaline conditions is expected to drop at approximately 19% of the year by 2050 (monthly variability: 21 – 36 g/L), and be minimized in the coming decades.
4 Synthesis and Discussion

4.1 Assessing the problem of GL salinization and associated restoration

The sections below (4.1.1 to 4.1.4) aim to provide a holistic approach to the problem of GL salinization, and provide answers to associated research questions (RQ1 to RQ4), based on the DPSIR framework.

4.1.1 Drivers and pressures (RQ1)

Human induced alterations to hydrology (drainage policies) along with climatic factors have been the major ‘drivers of change’ behind GL salinization (Paper I), similar to causes of salinization that have been observed worldwide (Perennou et al., 2012; Herbert et al., 2015; Jaramillo et al., 2018). GL salinization most likely started to occur in the mid-1970s, when the managers decided to flood the wetland with seawater as a strategy for re-establishing conditions for fishing in the lagoon. However, as the connectivity with the surrounding surface water bodies was not restored, the annual freshwater deficit of about 200 mm (due to prevailing climatic factors) has been primarily met by seawater inputs (Paper I). As a result, GL-W has been gradually transformed from a brackish to a seasonally hypersaline wetland (Paper II), a trend which has been observed in several Mediterranean and tropical wetlands (Perennou et al., 2012; Jaramillo et al., 2018).

High salinity has been highlighted in previous studies as one of the main factors leading to dystrophic crisis events and fish mortality in the GL (Arvanitidis et al., 1999; Koutsoubas et al., 2000), similar to other Mediterranean lagoons experiencing dystrophic crises after prolonged droughts (Obrador et al., 2008). Under future warmer and drier conditions, the period under hypersaline conditions in Gialova Lagoon is expected to be further prolonged, unless freshwater inputs are enhanced by restoring the hydrologic connectivity between the lagoon and the surrounding freshwater bodies (Paper II).

However, in the current context of water scarcity and competing water demands in the Mediterranean region, and Greece in particular (Pérez-Ruzafa et al., 2011; Klein et al., 2015; Destouni and Prieto, 2018), managing freshwater resources for the restoration of GL-W can be challenging. In Greece, the expansion of irrigation has significantly lowered runoff (Destouni and Prieto, 2018), resulting in less water being available for wetlands downstream of irrigated areas. Furthermore, water management associated with the expansion of tourism coupled with the effect of climate change, could lead to the reduction of groundwater storage and streamflow (Destouni and Prieto, 2018), resulting in environmental, social and economic impacts in the area (Klein et al., 2015).

During group discussions, the lagoon fishermen confirmed that olive-mills continue to dispose their wastes in Xerolagados river, and suggested that freshwater inputs from the artesian springs are more suitable to improve the lagoon status (Paper IV). However, Tyflomitis groundwater resources are used to cover the water supply of Pylos community, which comprises the local community and annual visitors, but the same resources are also used in agriculture, as many farmers irrigate their olive orchards (Paper IV). In fact, mean annual groundwater abstractions have gradually increased from approximately 6% of the aquifer’s natural recharge (1976-2000), to almost 41% (2001-2025), and are expected to increase up to 65% during the coming 25 years (Paper IV).

4.1.2 State (RQ2)

Under contemporary hydrological connectivity and on-going climatic conditions, the mean annual salinity of the lagoon has increased from approximately 35 g/L during the period 2016-2018 (paper II) to approximately 40 g/L during the period 2021-2023 (Gialova Project, 2023). The period under hypersaline conditions has therefore increased from 30% to approximately 50% of the year, which is a 67% increase, and is expected to increase even more under future warmer and drier conditions (Paper II, Paper IV). As also shown in previous studies (Arvanitidis et al., 1999; Koutsoubas et al., 2000), salinity varies
seasonally, with higher values during the dry period (June–October) and lower values during the wet period (November–March). However, in contrast to these studies the findings of this PhD study indicate that water conditions should be characterized as saline or even hypersaline from June to November, with more brackish conditions occurring during the wetter winter and early spring.

### 4.1.3 Impacts (RQ3)

**A. Hydrology**

Compared to climate-driven, long-term changes in salinity that have been recorded in the GL during the Holocene (Emmanouilidis et al., 2018), recent human induced alterations to hydrology have resulted in short-term, but more dramatic changes. For millennia the salinity of GL was regulated by the mixing of fresh water inputs from the catchment (Xerolagados river, artesian springs of Tyflomitis) with sea water inputs from the adjacent Navarino Bay, creating a brackish water body environment (Emmanouilidis et al., 2018). Under those conditions, the hydrological balance of the lagoon was most likely similar to those prevailing in ‘restricted’ lagoon ecosystems (Kjerfve and Magill, 1989), as the exchanges with the sea were occurring via a single sea-lagoon channel and the exchange flow was affected by both tidal activity and freshwater inputs from Xerolagados river and Tyflomitis artesian springs (Paper I). Compared to previous hydrologic conditions, the diversion of freshwater inputs in the 1960s – that remain to present days – has caused unprecedented changes on the hydrodynamics of the lagoon. The lagoon typology remains ‘restricted’ (Bray et al., 2022). Nonetheless under contemporary conditions, water exchanges with the sea occur mainly due to tide activity, a process that prevails in leaky lagoons where the exchange flow is via several inlets (Kjerfve and Magill, 1989).

In addition, the habitats within GL-W remain fragmented as human constructions separate the lagoon from the adjacent marshes, and the latter from the vegetated area of Tyflomitis artesian springs (Paper I). This fragmentation limits the water exchanges and constrains organisms’ mobility (e.g., fish, benthic organisms), but also creates stagnant waters and associated anoxic conditions (Bousbouras et al., 2011; Gialova Project, 2023).

**B. Ecology**

As reported above (section 3.1), the gradual salinization of the GL-W after 1976 had profound impacts on wetland vegetation cover and type, similar to alterations of hydrologic connectivity and consequent establishment of hypersaline conditions that have caused widespread mangrove mortality in tropical wetlands (Jaramillo et al., 2018). In the case of GL-W, the combined effect of increasing salinity (after 1976) and limitation in water circulation (after 1984–1985) has led to extensive reed and cattail mortality and expansion of halophytic species over the years, as much of the original habitats have been lost while in the remaining vegetated areas the brackish species were replaced by halophytic species. Similar to other wetland areas (Wang et al., 2011; Tavares et al., 2015; Brandis et al., 2018), the loss and degradation of wetland habitats has been one of the main reasons for declining waterbirds’ abundance within GL-W over the last 20 years (Paper III).

Apart from limitations in vegetation heterogeneity, salinity levels are critical for lagoon fish (Zoulas et al., 2017), which are vital in the food chain of several waterbirds (e.g., herons, ducks). The Mediterranean endemic *Aphanius fasciatus*, a species which is of priority for conservation within the EU, can tolerate salinity levels up to 65 g/L (Leonardos and Sinis, 1998). Sea bass can tolerate salinity levels up to 50 g/L, while sea bream and grey mullet can tolerate salinity levels up to 45 g/L (Algers et al., 2008). Salinity can affect the concentration of dissolved oxygen, the growth and especially the health and survival of fish which are adapted to prevailing salinity concentrations (Leonardos and Sinis, 1998; Algers et al., 2008). That is because above these levels fish need to consume additional energy to regulate their body functions and they become weaker.
C. Ecosystem services

Aforementioned alterations in GL-W hydrology and ecology, must have had profound impacts on wetland’s ES. Surface water regulation has been restricted as the flow of surface water resources is diverted to the sea. Water quality has also changed dramatically as at present day the lagoon has been transformed from brackish to saline (Paper I). Compared to pre-interventions time, ecosystem diversity has been limited to habitats covered by saline species or open water, waterbirds status is under decline, while the local fishermen are concerned as fish CPUE has been reduced by almost 30% (section 3.2.1).

The reduction in water circulation leads to the accumulation of organic material that is a habitat for the young stages of mosquitoes, and a deterrent to the presence of predators of their larvae, such as the species *Aphanius fasciatus* which is one of the most important predators (Leonardos, 2008). The latter in combination with the decline of migratory birds could lead to an excessive increase in mosquito populations. The effects of the above are significant in terms of the quality of the ecosystem, the aesthetics of the environment, and the health of residents and the visitors to the area.

4.1.4 Responses (RQ4)

To cope with salinization, future managers will need to consider the effect of climate change on GL-salinization and associated freshwater resources at multiple scales (Paper IV). The outcomes of the GL-SDM (climatic scenario RCP 4.5) indicated that at a lagoon scale, the pressure due to climatic conditions (annual freshwater losses due to evaporation) is expected to increase by ca. 50% during the short-term period (projected mean annual loss of about 280 mm/year), and become doubled during the mid- and long-term periods (projected mean annual loss of about 380 mm/year). At a catchment scale, projected climatic conditions are expected to reduce mean annual precipitation by approximately 3% and 12% during the short- and mid/long-term periods, respectively, while potential evapotranspiration is expected to increase by 9% and 14% during the same periods (Paper IV).

In principal, the problem of GL salinization is a matter of freshwater availability, and the simulations of the GL-SDM suggest that it could be ‘solved’ by restoring the hydrologic connectivity between GL-W and the surrounding freshwater bodies:

1. **Restoration of connectivity between lagoon, marshes and artesian springs (R1)**
   
   Based on the GL-SDM simulations, under current groundwater abstraction rates and projected climatic conditions (RCP 4.5) the restoration of connectivity between the lagoon and the artesian springs could be suggested as a first step towards stabilizing lagoon salinity at contemporary levels.

2. **Restoration of connectivity between the lagoon and Xerolagados river (R2)**

   To achieve the goal of lagoon de-salinization, there will be a need for additional surface freshwater inputs from Xerolagados river, and to that end the local industry will need to stop disposing wastes into the river.

4.2 Wetland restoration actions within the Natura 2000 framework (RQ5)

The restoration of hydrological conditions and wetland habitats within the GL-W is included as a water management measure in the revised Special Environmental Study of the GL Natura 2000 site (MM25510CJ0301 in Skokou and Chlykas, 2021), and to that direction the above-mentioned management suggestion (section 4.1.4) aspire to provide insights and ‘save’ precious time. Under current salinization trend, it is becoming urgent to implement actions to first mitigate the risk of a collapse (R1), and then regulate salinity to preferable levels (R2). However, prior to defining salinity preferable levels and restoration goals, future managers will need to consider both ecological and social values.

Located at the most south-western part of the Balkan Peninsula, along an important bird migration route (the Mediterranean/Black Sea Flyway), the GL-W is one of the few remaining Important Bird Areas along the south-west coast of Greece (Paper III). As such, the site is designated as a Special Protection
Area for birds under the Natura 2000 framework (GR2550008, 2001), and given the observed decline in waterbirds populations (Paper III), water management actions for restoring hydrological conditions and wetland habitats should aim to improve waterbirds “well-being” (MM25510CJ0301 in Skokou and Chlykas, 2021). Nonetheless, the lagoon provides food to the local community and fishing has been part of the local culture (Paper I). Thus, future managers will need to consider fish stocks and fishers’ needs as well (Paper IV). Tyflomitis artesian springs need to also be considered as an important wetland habitat for waterbirds’ conservation (Paper III), and the area should be maintained in a good state. To that end, managers will need to ensure that in the years to come, human abstractions from the Tyflomitis groundwater aquifer will remain below the “overall recharge of the aquifer not needed by the ecology”, as it is stated within the EUs’ Water Framework Directive (WFD, 2000/60). Consequently, an additional challenge for future managers will be to balance societal and ecological (conservation) needs, and promote groundwater management strategies that could enhance the sustainable use of water resources.

Considering the above, the suggestions for wetland restoration (section 4.1.4) aim to enhance biodiversity conservation, by considering nonetheless the existing human activities and social needs (e.g., fishing, groundwater abstractions for irrigation and domestic use), and linking to associated EU legislation for the management of Natura 2000 sites (Birds and Habitats Directives) and associated water resources (WFD.

The transition from saline to brackish conditions could create favourable conditions for the expansion of Phragmites australis (reeds), the basic nesting habitat for several waterbirds (e.g., Ixobrychus minutus, Casmerodius albus, Egretta garzetta, Tachybaptus ruficollis, Rallus aquaticus), including the nationally endangered Purple Heron (Ardea purpurea) and the Ferruginous Duck (Aythya nyroca), a species that is considered as vulnerable at a European level (Paper III; Bousbouras et al., 2011). Such a transition could be possible as it was observed in another Mediterranean wetland, where the increase in freshwater inputs has favoured the expansion of reeds over existing halophytes (Álvarez-Rogel et al., 2007).

Based on the outcomes of the GL-SDM, the time with favourable conditions for reeds (monthly salinity below 22.5 g/L according to Lissner & Schierup, 1996; Sánchez-García et al., 2017;) could be expanded to all year around (Paper IV). Nonetheless, the local fishers argued that an uncontrolled drop of salinity levels could impact the fishing activity in the lagoon (3rd sectoral workshop). Hence, they would welcome lagoon de-salinization actions to levels around 30 g/L (mean monthly variation between 20 and 40 g/L), which could increase the time with favourable conditions for reeds up to 40% of the year, but they would like to avoid salinity levels below 20 g/L, at least for extended periods of time, because fish ‘get an awkward taste’ which lowers their market value (Paper IV). The latter, although vague, should not be neglected by future managers as it could lead to emerging trade-offs and delays in implementation similar to what has happened in the past (HOS, 2000). To reduce the risk of conflicts, the GL-SDM could be further utilized to simulate scenarios under different salinity goals (Paper IV), and support discussions among involved SHs (e.g., fishermen and conservationists).

Furthermore, the GL-SDM outputs indicate that the re-connection of the marshes with the artesian springs, along with the restoration of connectivity between the lagoon and the marshes (e.g., partial replacement of the inner embankment by a bridge to allow free water flow between water bodies), is expected to increase the connectivity between GL-W habitats by approximately 34% (lagoon-marshes-springs), and the open water for fishing area by approximately 27%, whilst leading to improved water circulation within the wetland (Paper IV). Aforesaid restoration actions could be promoted as an example of win-win solutions between fishermen and conservationists (or Natura-2000 site managers), as lagoon fishers could increase their fish CPUE (larger fishing area), while ecosystem restoration (de-fragmentation) is a key conservation measure within the recently validated Natura 2000 management plans (MM25510CJ0301 in Skokou and Chlykas, 2021). In addition, the restriction of stagnant waters could reduce the risk of excessive increase in mosquito populations, and especially of the species Aedes...
albopictus (tiger mosquito), which according to the World Health Organization can carry many diseases and increase the risk for human health (WHO, 2023).

Overall, the restoration of wetland habitats and the regulation of hydrological flows is expected to increase the diversity of habitats and enhance fish and waterbirds ‘well-being’. In terms of economics, the restoration of Gialova Lagoon should be considered as a profitable investment according to the European Commission, every €1 invested into nature restoration may add €8 to €38 in benefits (European Commission, 2023d). In addition, biodiversity conservation could support the development of alternative forms of tourism on site, namely bird-watching, sport-fishing, and nature appreciation, and meet the local demand for diversified incomes through the development of eco-tourism (Paper IV). Such activities could enhance the bonds between people (local community, visitors) and nature, and further support conservation actions. For instance, bird-monitoring projects have been among the most successful at integrating citizens in collecting data (McCaffrey, 2005), leading to successful long-term monitoring projects in Greece (HOS, 2023) and worldwide (Chandler et al., 2017). However, eco-tourism activities could also disturb wildlife (Cardoni et al., 2008; McFadden et al., 2017), and they need to be organized carefully (e.g., not allowed during the breeding period).

To address the challenge of groundwater scarcity, the GL-SDM could provide insights to future managers as the simulated scenarios have assumed a variety of water-saving approaches, which have been recommended by local stakeholders (Table 5). As described in Paper IV, coordinated efforts to mitigate freshwater abstractions for irrigation and municipal water-supply could foster the resilience of the society against groundwater scarcity. Compared to current groundwater abstractions and associated projected trends, the GL-SDM simulations show that groundwater managers could save up to approximately 370,000 m³/year during the short-term period (2026-2050), up to approximately 580,000 m³/year during the mid-term period (2051-2075), and more than 680,000 m³/year during the long-term period (2076-2100). The model outcomes further suggest that groundwater availability for ecosystems’ support is sustained to levels above 55% of the aquifer recharge during the whole simulation period, which is a fundamental objective of WFD (2000/60).

4.3 A decision-support-system-tool towards the co-management of GL Natura 2000 site (RQ6)

The restoration of natural flows for regulating lagoon salinity was proposed as an important management action towards wetland restoration already at the end of the last century (Koutsoubas et al., 2000). However, the 1999 efforts for enrichment with surface freshwater bodies have failed in practice as the limited inclusion of stakeholders in decision-making, along with the absence of a clear management scheme and restoration goals, created conflicts among the water users which sabotaged the actual implementation (Paper I, Paper IV). To cope with emerging trade-offs, the European Commission recognizes that the successful management of Natura 2000 sites requires effective coordination between a range of sectors at a site level (ECA, 2017; CEEweb, 2019), as the participation of stakeholders in decision making facilitates legitimacy in the process (Gopnik et al., 2012), and in turn may also affect compliance positively. Thus, most EU environmental directives (e.g., WFD, Birds and Habitats Directives) promote and require – to different extend – the participation of local stakeholders and citizens in decision making (McGuinn et al., 2017).

To that extend, the work under this PhD aspires to provide a pilot to future managers on how to address complex environmental challenges within the GL-SES, engage stakeholders in decision making, and promote environmental co-management of the Natura 2000 site. Figure 12, illustrates the overall approach of this work which was based on the integration of DPSIR framework, with the process of participatory SDM and the concept of ES. In environmental management, several studies have combined the DPSIR framework with SDM approaches or the concept of ES. For example, integrated DPSIR-SDM
approaches have been applied in fisheries management as well as in management of water resources and wetlands (Camanho et al., 2010; Chen et al., 2014; Zare et al., 2019), while DPSIR-ES approaches have been applied as a way to manage biodiversity and associated benefits to humans (Shiyu Li and Chang, 2015; Xue et al., 2015).

In this study, the DPSIR framework was applied to assess the problem of salinization, based on systems-thinking and cause-effect relationships between interacting components within a social-ecological system (Bradley, 2015). The concept of ES provided the linkages between nature and human well-being (Maes et al., 2022), and was utilized to translate the ecological components of GL-SES into management elements. Participatory SDM promoted the common understanding between scientists and stakeholders (integration of scientific and local knowledge) and provided the conceptualization of linkages between social and ecological components within the GL-SES in a structured manner.

As indicated in Paper IV, the participatory SDM process was not only useful for designing and validating the model (and associated management suggestions), but it also contributed in the co-creation of a common understanding among the different stakeholders and the creation of a shared vision for the sustainable development of the area. Above all, it provided the social learning space that allowed for the expression of the multiple perceptions and expertise, a platform for discussions which is essential in co-management approaches (Kofinas, 2009; Fabricius & Curries, 2015). In essence, the end product (GL-SDM) is a decision-making tool that builds on the integration of scientific and local knowledge, and could be applied as a decision-support-system-tool for the restoration of the GL-W’s hydrological conditions and habitats.

**Figure 12.** Graphical conceptualization of the DPSIR-SDM-ES approach which was followed in this PhD study (ES highlighted with *italics*). The flow of the SD model is from left to right to depict the directional change from a reference (natural) to a degraded state. The structure of the SD model starts from ‘Drivers’ and ‘Pressures’, which are connected to ecosystem ‘Status’ and ‘Impacts’ on associated ES. The necessary feedback loops within the SDM are generated by ‘Responses’ which have a direct effect on different elements of the GL-SES, as suggested in the DPSIR framework. In essence, the feedback loops of the SDM are the suggestions for wetland restoration and management of associated freshwater resources, which have been co-developed during participatory SDM exercises.
5 Suggestions for future work

With a delay of approximately 20 years, the management of the GL-W has been assigned to a public Management Body (OCG, 2020), hopefully bringing an end to an odyssey of mis-management. The management suggestions derived from this PhD thesis aspire to support the implementation of "Water Resources Management Measures" under the project "Implementation of Special Environmental Study and Management Plans for the Natura 2000 sites of Peloponnese region (Greece)" of the Ministry of the Environment and Energy with codes (Skokou and Chlykas, 2021):

- MM25510CJ0301: Action plan for the restoration of hydrological conditions and wetland habitats in the Gialova lagoon.
- MM25510CJ0201: Management decision support system in the Gialova Lagoon to achieve Favourable Conservation Status in the wetland.

With regards to MM25510CJ0301, the PhD thesis has shown that in theory the restoration of natural flows with the surrounding surface freshwater bodies, could fulfil the demand for freshwater inputs towards lagoon de-salinization, and restoration of wetland habitats. However, prior to implementation of restoration work future managers will need to consider the technical aspects of the interventions. For instance, a detailed study on the wetland’s water dynamics and circulation could ensure that the interventions will be designed in a way that will allows the free flow between the water bodies, considering that severe water level fluctuations during the waterbirds’ breeding period (April to June), could flood the nests (Paper III). To that direction, a study on the topography of the area could also provide useful insights to associated managers.

With regards to MM25510CJ0201, the co-development of the GL-SDM could be used as a platform for designing a decision-support-system associated to salinity regulation within the wetland. To further enlarge the applicability of the model in decision making, it would be necessary to study the effect of agriculture on wetland eutrophication, as the lagoon is at a poor ecological state due to increased inputs of nutrients from conventional agricultural activities which occur within the catchment (Bray et al., 2022; Berg et al., 2018). Towards that direction, future research could aim to describe how the transition from conventional to agroecological cultivation practices (e.g., cover-crops) could mitigate the impact of olive-oil production on groundwater resources (e.g. fewer nutrient loads), and how this transition could be beneficial for farmers’ livelihoods (e.g., better olive-oil quality, increased possibilities for branding, compliance with EU directives, engagement of youth etc.). Furthermore, a detailed study on irrigation practices at a catchment scale could provide more accurate data and improve the simulations of the GL-SDM with regards to freshwater availability.

The DPSIR-SDM-ES approach followed within the thesis, integrates scientific and local knowledge in the restoration and management of GL-W and promotes the adoption of co-management approaches as recommended in the national “Framework of Priority Actions for the Natura 2000 Network” (PAF_EL, 2021-2027). For the scope of this thesis, the focus was primarily on ES at a wetland scale (e.g., fishing, ecosystem diversity, waterbirds), but it could be applied at wider scales based on insights from future assessments on ecosystem services.
6 Conclusions

Past man-made interventions had multifold effects on the Gialova Lagoon wetland, namely ecosystem fragmentation, loss and transformation of natural habitats, while the combined effects of human interventions and climate have led to increased salinity in the wetland over time. The vegetation cover has been reduced by approximately 47%. Since part of the vegetation has been covered by water, the open water cover within the wetland has increased by almost 23%. In the long run the brackish species in the remaining marshes were replaced by halophytes due to salinization. Overall, these alterations had profound implications on wetland Ecosystem Services such as the diversity of habitats and waterbirds abundance and the provision of fish. The results of the study suggest a current salinization rate of approximately 1 g/L per year (2017-2022). Respectively, the period under hypersaline conditions has been increased from 30 to approximately 50% of the year. Under future warmer and drier conditions, the period under hypersaline conditions is expected to be prolonged, unless freshwater inputs are enhanced by restoring hydrologic connectivity between the lagoon and the surrounding freshwater bodies.

In the context of a degraded coastal lagoon, where the implementation of restoration actions under the Natura 2000 framework has failed in practice, the GL-SES represents an example of complex social-ecological interactions that need to be managed. To provide policy recommendations for wetland restoration and management of associated freshwater resources, the PhD thesis has followed a participatory SDM approach, which was much appreciated by the engaged stakeholders as such processes have never occurred in the area before. The outcomes of the GL-SDM suggested that the restoration of connectivity within the wetland (lagoon-marshes), and with Tyflomitis artesian springs and Xerolagados river (partly) could result in lagoon de-salinization within a 10-year period, regardless efforts to decrease groundwater abstractions upstream. However, under current abstraction rates for irrigation and water-supply (local community, tourism) there is a risk of groundwater scarcity during years with dry conditions. On the other hand, a sustainable management of groundwater abstractions could save some 350,000 to 650,000 m³/year, increasing the resilience of the local economy under expected climate change, while ensuring adequate discharge at Tyflomitis artesian springs.

Overall, the results of this PhD showcase that “restoring connectivity” within the social-ecological system of GL-W in terms of physical (e.g. restoration of natural flows), ecological (ecosystem de-fragmentation), and social (bringing together SHs from different sectors) connectivity, is an “umbrella” action towards sustainability in the area. Based on the experience gained during this PhD, it takes time and energy to build trust and understanding among the different stakeholders, and apart from pure scientific work (e.g. data collection and analysis), a fundamental role for the researcher/manager should be to facilitate discussions with associated stakeholders, comprehend their views and concerns, and promote decision-making based on co-management approaches.

Last but not least, the followed DPSIR-SD-ES approach, is in line with national recommendations for environmental management of Natura 2000 sites, and it could be applied by future managers to assess a variety of environmental issues within the GL-SES. As the approach is based on well-established concepts and methods, it could be replicated to other coastal ecosystems within Greece and the Mediterranean.
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References


