Studies on water resources salinization along the Italian coast: 30 years of work

Studi sulla salinizzazione delle risorse idriche lungo le coste italiane: 30 anni di lavoro

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La densità della popolazione lungo le coste italiane è doppia rispetto alla media nazionale. Lungo la costa si trovano numerosi insediamenti urbani, economici e produttivi, che in molte zone hanno alterato le caratteristiche naturali del territorio. Inoltre, recenti studi sui cambiamenti climatici prevedono grandi impatti sul ciclo idrologico nel Mediterraneo. Pertanto, nei prossimi anni, le risorse idriche in aree costiere saranno sottoposte ad una pressione crescente. Questo a sua volta può tradursi in una progressiva salinizzazione, un fenomeno diffuso e preoccupante in tutto il mondo. In questo articolo verrà discussa in maniera critica la distribuzione storica e geografica degli studi peer-review incentrati sulla salinizzazione delle risorse idriche lungo le coste italiane.

The population density on the Italian coasts is twice the national average. Numerous urban, economic, and productive settlements lie along the coast, which in many areas have altered the natural characteristics of the territory. Moreover, recent climate change studies forecast large impacts on the hydrologic cycle in the Mediterranean. Thus, in the next years, coastal water resources will be gradually more stressed. This in turn may result in a progressive salinization, which is a widespread and worrying phenomenon worldwide. In this paper, the historical and geographical distribution of peer-review studies focusing on the salinization of water resources along the Italian coasts will be critically discussed.

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Introduction

The Mediterranean basin showed large climate change (CC) in the past (Luterbacher et al. 2006) and model projections suggest that it will be a “Hot-Spot” in future CC (Giorgi and Lionello 2008). Given its geographical position, there is no doubt that Italy will be affected by these changes. The forecasted CC impacts could have adverse effects on water resources (Ketabchi et al. 2016), terrestrial and marine ecosystems (Walther et al. 2002), human activities (McMichael et al. 2007), and health (Patz et al. 2005). In particular, a gradual depletion of surface water (SW) and groundwater (GW) due to pollution and increasing demand for intensive agriculture, demographic and economic growth is expected (Foster and Chilton 2003). This will be particularly noticeable in coastal areas, already prone to large environmental, economic, and social stresses. About 30% of the Italian population lives along the coast, with an uneven distribution since most of it is concentrated in the fertile coastal plains, where the density of inhabitants can reach peaks of 10,000 in/km², like in the metropolitan area of Naples (ISTAT 2020). Additionally, over the Italian peninsula, SW and GW resources are not homogeneously distributed, so that the eventual increase in their exploitation may result in water scarcity (ISPRRA 2020). This vision urges the research on water salinization, and the definition of strategies to minimize its impacts in the near future. The main purpose of this paper is to present the knowledge achieved by the research studies concerning the salinization of water resources in Italy, discussing what has been done and what still remains to do to better manage this valuable resource.

Materials and Methods

To select the studies considered in this work, a search in the Scopus database (Elsevier) was conducted using various combinations of the following keywords: water resources, salinization, seawater intrusion (SWI), coastal aquifer, saltwater wedge. From a spatial point of view, only studies at a maximum distance from the coast of about 50 km were considered, while no time limits were attributed to the search. Of the 179 studies analysed (Fig. 1A), only some will be explicitly mentioned in the paper not to burden the discussion and because they were considered more representative. The 179 studies have been classified according to seven different information: the location of the field sites (Fig. 1B), the main topic addressed (Fig. 1C), the type of substrate (Fig. 1D), the data acquisition techniques (Fig. 1E), the data handling methodologies (Fig. 1F), the areal extension of the study (Fig. 1G), and the time of publication (Fig. 1H). It must be pointed out that the categorization was done with the simple aim of constructing a logic pathway to analyse the literature in this specific field, but since this choice is inherently subjective a large overlap is possible between categories.

Results and Discussion

Spatio-Temporal Distribution of the Studies

The 179 studies analysed spread over a period of 30 years, from 1992 to 2021 (Fig. 1H). In the first decade only 4% of the studies were published and they mainly focused on the simple recognition of the salinization of water resources in a given area, addressing only the occurrence of water salinization without identifying the source that induced salinization (e.g., SWI, water rock interaction, up coning of paleo seawater, etc.) and without investigating the mechanisms that induce an increase in the salt content (e.g., transport of dissolved species, dissolution, evapoconcentration, etc.). In the second decade 25% of the studies were published, mainly focusing on the origin of salinization and on the mechanisms governing the phenomenon. The last decade involved the publication of 71% of the studies, which also addressed for the first time the quantification of the impact of salinization on different assets, the estimation of future projections, and the search for possible solutions to the problem.

Concerning the geographical distribution of the studies (Fig. 1B), most of them (43%) were performed in the Po delta (considered as its maximum extension in the Holocene) and among them the majority was published in the last decade. A large number of studies were performed in Sicily and Sardinia (12%), in the Upper Thyrrenian (11%) and in the Murge-Salento (10%). An interesting aspect to underline concerns the extension of the areas covered by these studies and again the geographical distribution of the more extensive studies (Fig. 1G). Most of the studies extend over 10 to 100 km² and are equally distributed throughout the Italian peninsula. Studies covering small areas are quite common (32% considering both 0.1-1 km² and 1-10 km² classes) and are mostly located in the Po delta, specifically in the Emilia-Romagna region where hot spots of salinization were detected and where the studies have been often performed in order to find solutions to protect or restore specific sites. In the same area, most of the studies extending over 100 to 1000 km² were also performed. Regional studies extending more than 1000 km² are only 10% and they are almost entirely located in the Murge-Salento region, where salinization of water resources is an urgent issue already posing a serious threat to human activities.

Finally, considering the type of aquifer investigated (Fig. 1D), 81% of studies were performed on porous aquifers and only 19% on fractured aquifers. For the porous aquifers, the largest number of studies concerns the main deltas of the Italian peninsula (47%), while in the fractured aquifers most of the studies investigate karst aquifers and once again most of them are in the Murge-Salento region. The smaller number of studies on karst massifs respect to the alluvial aquifers is probably due to the inherent technical complexities and high costs that characterize the field activities.
Data acquisition and handling

Among the 179 papers considered, few studies were performed via off site data acquisition (10%) (Fig. 1E). Barbarella et al. (2015) used satellite ASTER data to assess the effects of SWI on coastal pinewood vegetation, while airborne electromagnetics methods (AEM) were employed to identify SW-GW exchange in the Venice Lagoon (Viezzoli et al. 2010). On the other hand, few studies were performed in laboratory conditions to understand specific mechanism influencing saltwater distribution in the field, like the complex biogeochemical processes that occur between buried peaty lenses and the flowing through GW (Colombani et al. 2016a).

Moving to field-based monitoring strategies, the direct acquisition of water and/or soil samples (77%) is by far more employed than the indirect acquisition via geophysical techniques (13%). Within this last group, the Vertical Electrical Sounding (VES) (Balia et al. 2008), the electrical resistivity tomography (Greggio et al. 2018), and the time-lapse electrical resistivity tomography (De Franco et al. 2009) have been largely used together with geological and hydrogeological data to map zones characterized by high salinities and their dynamics. Often geophysical methods have been coupled with geochemical data (Cimino et al. 2008) to calibrate indirect acquisitions and to provide more robust information. When a direct collection of water and/or soil samples was planned, in most cases the sampling was carried out in pre-existing wells by means of standard integrated depth sampling, while the studies carried out via dedicated
Multi-Level Samplers (MLSs) were far less numerous, though they allow a correct vertical discretization which is essential in complex transitional coastal areas (Mastrocicco et al. 2012).

Several papers have focused on the origin and distribution of GW salinization by means of a detailed geochemical study using major ions and selected trace elements, both in porous (Pittalis et al. 2016; Summa et al. 2019) and fractured aquifers (Sappa et al. 2019; Ghiglieri et al. 2009). To further increase the potential in distinguishing the mechanisms of GW salinization, different major ions ratios were employed (Bonamico et al. 2021; Zancanaro et al. 2020). Together with the ion ratios approach, a widely used technique to disentangle the origin of GW salinization is the employment of environmental isotopes (Mongelli et al. 2013; Caschetto et al. 2017).

Even though most papers (51%) rely on the sole analysis of the collected hydrogeochemical information (Fig. 1F), a widely applied approach to evaluate GW salinization is surely the use of geostatistical methodologies (21%) like: i) Monte Carlo approach to evaluate SWI (Lecca and Cau 2009); ii) drought indices to qualitatively infer the aquifer salinization trend (Alfio et al. 2020); iii) probabilistic framework to reproduce SWI (Felisa et al. 2015); and iv) risk assessment methods and fuzzy cognitive maps to analyse the impact of agricultural activities on aquifer salinization (Zaccaria et al. 2016).

A more complex and data requiring approach is the one that makes use of numerical models (28%) (Fig. 1F). They have been widely used to quantify the different origins of salinization via density dependent flow and transport models, starting with simple applications in the past (Bixio et al. 1998) to more complex simulation combining numerical models with geophysical methods (Masciopinto et al. 2017), with complex reactive transport software (Campana and Fidelibus 2015), or with both (Vespasiano et al. 2019).

Whatever the methodology used to acquire and handle the dataset, it can be stressed that there is a net prevalence of the spatial analyses (Polemio 2016) with respect to the temporal trend analyses (Giambastiani et al. 2020), since it is more challenging to obtain consistent hydrochemical information for long time periods.

**Detailed Analysis of the Topics Covered in the Studies**

The 179 studies have been summarized in seven main categories based on their main topic (Fig. 1A): (i) sole identification of water resources salinization and/or description of monitoring techniques; (ii) origins and mechanisms governing water salinization; (iii) environmental, economic and social impacts of salinization; (iv) predictive studies on water quality in coastal areas; (v) vulnerability and risk assessment; and (vii) solutions to counteract progressive salinization.

**Identification of the phenomenon and monitoring techniques**

Most studies focusing on the sole identification of water salinization date back to ‘90s and most of them make use of geophysical techniques to gain the information needed to map salinity distribution. One of the first studies relying on hydrogeochemical analysis was performed in Tuscany (Giménez et al. 1996). More recently, Masciopinto et al. (2017) address the issue of GW salinity mapping in fractured coastal aquifers, via the aid of numerical simulation, while Mastrocicco et al. (2012) discuss the importance of data acquisition techniques in SWI monitoring.

**Origin and mechanisms governing water salinization processes**

Studies that have addressed the origin and mechanisms of salinization are the largest group (40%; Fig. 1A) and have been published from 2008 onwards. In most studies several concomitant causes have been identified (Mastrorillo et al. 2016; Mongelli et al. 2013), showing the complexity of this phenomenon. A large number recognize water rock interactions (Campana and Fidelibus 2015; Sappa et al. 2019) and actual SWI both from underground (Gattacecca et al. 2009; Vespasiano et al. 2019) and surficial flows via rivers and canals (Franceschini and Signorini 2016) as the major salinization mechanisms, usually employing hydrogeochemical characterizations. Less studies have pointed other processes like: paleo-seawaters up coning (Colombani et al. 2017), geo-thermal sources (D’Alessandro et al. 2017), sea salt aerosol (Manca et al. 2015), and recurrent drought (Alfio et al. 2020). In many studies, over-pumping or excessive artificial drainage (Barazzuoli et al. 2008; Grassi et al. 2007), if not identified as the main cause of salinization, are however always considered as an extremely detrimental factor for water quality, as the lowering of the water table favours both SWI and the upwelling of waters with high relict salinity.

**Impacts of water resources salinization on natural systems**

Along the Italian coast, a variety of impacts induced by increasing salinization of SW and GW were reported in the most disparate environments. The best documented impacts refer to: i) soil salinization promoted by SWI and irrigation with unsuitable waters (Vittori Antisari et al. 2020; Castrignanò et al. 2008), which in some cases are explicitly correlated with a decrease in crop yield (Leogrande et al. 2016); ii) the stress and mortality in pinewood coastal vegetation induced by high salinity levels in shallow GW (Barbarella et al. 2015), and the decrease in vegetation species richness (Antonellini and Mollema 2010; Gerdol et al. 2018); and iii) the increase mobility of trace elements which can even lead to exceeding the permitted limits (Pezzetta et al. 2011; Protano et al. 2000). Studies on the impact on microbial and macroinvertebrate communities are rarer and usually focus on SW salinity (Muresan et al. 2020). Finally, an interesting and innovative branch discusses the impact of SWI on valuable or ancient artifacts (Di Sipio et al. 2011; Stellato et al. 2020) pointing out that sea-salt damages on different building materials may be widespread and need to be kept under control to preserve cultural heritage in coastal areas.
Prediction of salinization trends and vulnerability assessment

Most studies employed numerical flow and transport models to simulate future salinization trends induced by CC in SW (Bellafiore et al. 2021) and GW (Masciopinto and Liso 2016), or by changes in land use (Mastrocicco et al. 2019) and GW exploitation (De Filippis et al. 2016). A different approach has been followed by Parisi et al. (2018) where climatic drivers like meteorological droughts are proposed as cascading events that trigger aquifer salinization. Similarly, Benini et al. (2015) used climatic balances from predicted CC scenarios to derive a vulnerability index to salinization. The assessment of the vulnerability to salinization via GIS weighting and rating methods was further implemented for low lying areas accounting for the role of SW bodies (Kazakis et al. 2019) and subsidence rate (Da Lio et al. 2015). The main advantage of these methods, with respect to numerical simulations, is the relative easiness to handle high amount of data in a GIS environment, even though they are highly user dependent and cannot reproduce temporal evolution. Finally, a study from Colombani et al. (2016b) predicts salinization trends according to forecasted CC in the Po delta, and the trend of heavy metal release triggered by the increased salinity.

All approaches used to predict future trends in water quality in the abovementioned studies are affected by uncertainties due to: (i) variation of the surficial and underground morphology and flow regime (e.g., subsidence, coastal erosion, lack of recharge), (ii) poorly known stresses (e.g., future pumping rates and land use changes), (iii) inherent uncertainties of CC projections. Nevertheless, these studies often quantify the uncertainties linked with the unknown variables (sensitivity analysis) and account for different scenarios considering the most probable conditions, thus providing information on future hydrodynamic and biogeochemical behaviours which are essential for planning countermeasures to address in advance future adverse impacts related to the salinization of coastal water resources.

Possible solutions to the salinization issue

The studies that present strategies and/or technologies to prevent or mitigate water salinization are not numerous (10%). A study from Antonellini et al. (2015) reports GW freshening following coastal progradation and land reclamation and highlights that this trend could be strengthened by appropriate management of the drainage network. An interesting study on farmed coastal plains at risk of salinization proposes changes of irrigation deliveries by the water users' organization to counter farmers' propensity to pump GW, rather than rely on rotational deliveries (Zaccaria et al. 2016). For fractured aquifers, the identification of critical threshold for GW exploitation (Cherubini et al. 2011; Nocchi and Salleolini, 2013) and the definition of effective MAR strategies (Polemio and Zuffianò 2020; De Filippis et al. 2019) has been proposed.

Discussion

The number of studies on water resources salinization has grown fast in the last decade in Italy but there is a large inequality in their spatial distribution, with areas that have not yet received the appropriate attention and areas investigated in detail (Po delta and Murge-Salento). Moreover, there is still a lack of studies addressing the temporal variations in GW quality. Most papers emphasize the role of human perturbation on coastal system, in fact even where salinization processes are occurring naturally the human activities tend to accelerate these processes. For instance, many papers reported strong signals that some aquifers, especially karst ones, are critically overexploited and that corrective actions must be undertaken, eventually at the whole watershed scale. Studies addressing the impacts of water salinization on GW dependent ecosystems (coastal wetlands, forests, lagoons, and their fauna) and social dimensions (agricultural, industrial, and urban) are just a few, thus there is the urgent need to build conceptual (and possibly numerical) models that include these assets to better manage coastal water resources. Accordingly, more studies focusing on predictions of CC impacts on coastal SW and GW are needed to give direction to future prevention and mitigation interventions.

Conclusions

The integrated coastal aquifer management is a key issue that must be tackled in the near future to defend freshwater resources in presence of CC and the related land use changes along the Italian coast. The major goal for the coming research will be to provide studies that widen the local perspective towards the regional one and to obtain long-term series of off-site and on-site data. To tackle this challenge, a common monitoring strategy should be started aiming to gain publicly shared database that could be used by both the academic and professional communities to manage coastal aquifers.

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Competing interest

The authors declare no competing interest.

Author contributions

Micòl Mastrocicco: Conceptualization, Methodology, Writing and Editing.

Additional information

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