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Groundwater footprint methodology as policy tool for balancing water needs (agriculture & tourism) in water scarce islands - The case of Crete, Greece

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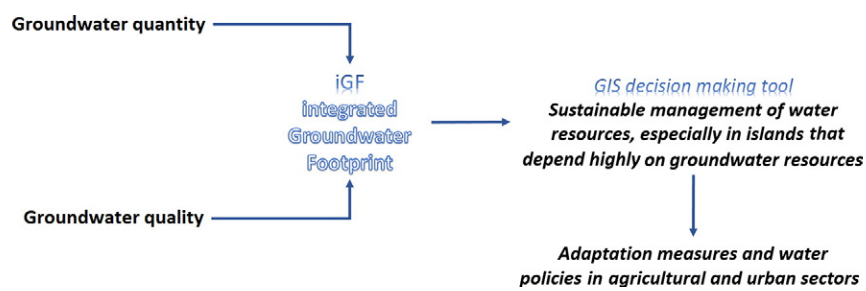
HIGHLIGHTS

- A novel approach for groundwater footprint estimation was introduced that incorporates water quality.
- A case study in the water scarce island of Crete was presented.
- From the 11 groundwater systems in Crete, three have iGF/A values above one (Chania, Iraklio, and Sitia).
- The average value of iGF/A for all aquifer systems in Crete is very good (0.649).
- Adaptation measures and water policies in agricultural and urban sectors were presented.

GRAPHICAL ABSTRACT



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ABSTRACT

In many Mediterranean islands with limited surface water resources, the growth of agricultural and touristic sectors, which are the main water consumers, highly depends on the sustainable water resources management. This work highlights the crucial role of groundwater footprint (GF) as a tool for the sustainable management of water resources, especially in water scarce islands. The groundwater footprint represents the water budget between inflows and outflows in an aquifer system and is used as an index of the effect of groundwater use in natural resources and environmental flows. The case study presented in this paper is the island of Crete, which consists of 11 main aquifer systems. The data used for estimating the groundwater footprint in each system were groundwater recharges, abstractions through 412 wells, environmental flows (discharges) from 76 springs and 19 streams present in the area of study. The proposed methodology takes into consideration not only the water quantity but also the water quality of the aquifer systems and can be used as an integrated decision making tool for the sustainable management of groundwater resources. This methodology can be applied in any groundwater system. The results serve as a tool for assessing the potential of sustainable use and the optimal distribution of water needs under the current and future climatic conditions, considering both quantitative and qualitative factors. Adaptation measures and water policies that will effectively promote sustainable development are also proposed for the management of the aquifer systems that exhibit a large groundwater footprint.

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1. Introduction

In the past few decades the environment and especially water resources have been experiencing significant stress, resulting in water related problems in many regions around the world. The surface and groundwater resources are continuously degraded as a result of agricultural activities (agrochemicals, herbicides, livestock wastes etc.), industrial wastes, as well as urban and touristic activities (Vorosmarty et al., 2000; Oki and Kanae, 2006; Giordano, 2009; Wada et al., 2012; Dokou et al., 2015).

Sustainable management of water resources should be a top priority in the design of any water management system. In order to assess water resources and detect potential threats and problems, the scientific community has developed various indices, such as the ecological and water footprint as well as a more specific index for aquifer systems, namely the groundwater footprint (Hoekstra et al., 2011; Roelich et al., 2014; Pedro-Monzonís et al., 2015; Lovarelli et al., 2016; le Roux et al., 2017). The ecological footprint refers to the ecological assets (plant-based food and fiber products, livestock and fish products, timber and other forest products, space for urban infrastructure etc.) needed by a given population in order to produce the natural resources it consumes, taking into account the space needed for waste disposal and carbon emissions. In other words, it represents the required land area needed to sustain a given population (Wackernagel and Rees, 1996; Hoekstra, 2009).

In 2002, the water footprint concept was introduced to the scientific community by Hoekstra and Hung, 2002. The water footprint of a product is the volume of water consumed and polluted in all stages of its production, providing an estimate of how much pressure that product has put on freshwater resources (Hoekstra and Chapagain, 2007). It can also be measured in volume of water used in specific period e.g. per year (Hoekstra, 2009).

The water footprint shows the extent of water use in relation to its consumption. A water footprint has three components: green, blue and grey (Hoekstra, 2009; Lovarelli et al., 2016): a) the blue component refers to the volume of surface and ground water resources consumed (assuming that their volume of water does not return to the same region e.g. the same watershed), b) the green component refers to consumption of rainwater absorbed as soil moisture and consumed by the process of evapotranspiration (particularly relevant in crop production), and c) the grey component, defined as the volume of freshwater that is required to dilute the load of pollutants based on existing water quality standards, serving as an indicator of the degree of freshwater pollution. Based on the above, it is evident that water footprint (WF) is an index that incorporates the volume of water being polluted during all stages of a product's production. Moreover, it does not only estimate the total volume of water consumed but accounts for the source of the water and the time period during which it was consumed (Pellicer-Martínez and Martínez-Paz, 2016). The WF is a powerful tool for the optimal management of water resources, especially in agricultural and touristic regions with limited water resources. Hoekstra and Chapagain (2007) calculated the global WF on a national scale based in data for the period 1997–2001. According to their work, of great interest is the rank of Greece which reaches 2389 m^3/cap/y, being the second largest WF after the United States and double that of the global mean (1243 m^3/cap/y). This is attributed mainly to the increasing water used for agriculture (85%), to significant losses due to the old irrigation and water supply network and the mismanagement of water resources in general in the country (Water Resources Department of the Prefecture of Crete, 2014).

Up to now, the majority of research related to the water footprint has focused on the volume of water required for various activities, while limited studies have been performed on the quantity of water available (Hoekstra et al., 2012; Gleeson et al., 2012; Xinchun et al., 2017). The groundwater footprint (the area required to sustain groundwater use and groundwater-dependent ecosystem services), is a complementary policy tool to the well-established water footprint method and can be used to evaluate the effect of groundwater consumption on natural flows. The groundwater footprint can be defined as the area required for sustainable use of groundwater for a region, such as a watershed, an aquifer, or a community. It is useful tool for assessing the use, replenishment and ecosystem requirements of groundwater at an aquifer scale (Gleeson et al., 2012). It has been estimated that the global groundwater footprint is $131.8 \pm 24.9 \times 10^6$ km^2, or 3.5 ± 0.7 times the real area of the hydrological active aquifers (BGR/UNESCO, 2008; Gleeson et al., 2012). Moreover, according to Rodell et al. (2009) and Xinchun et al. (2017), 1.7 ± 0.4 billion people live in areas where groundwater consumption can influence their supplies in the future, with 60% living in India and China.

The proposed groundwater footprint methodology is applied to hydrologically active aquifers located in islands that depend highly in groundwater resources to meet increasing water demands. This methodology incorporates, for the first time, the groundwater footprint both in terms of quantity and quality, establishing an integrated approach for estimating groundwater footprints for aquifer systems that exhibit significant water demands as well as degradation due to contamination. The proposed groundwater footprint method can be applied to a variety of scales and hydrogeological systems and can be used as a useful management tool for balancing water consumption, especial in water scarce islands with intensive agricultural and touristic development.

2. Study area

The study area of this case study is the island of Crete, the fifth largest island in the Mediterranean Sea and the largest in Greece, with a total area of about 8265 km^2. The island of Crete includes Chania, Rethymnon, Heraklion, and Lassithi prefectures. The elevations in Crete are highly variable ranging from zero to 2456 m MSL. The lowland areas (<200 m) cover an area of approximately 2165 km^2 (26% of the total area), the semi-mountainous areas (200–800 m) cover an area of about 4627 km^2 (56% of the total area) and the mountainous areas (>800 m) cover an area around 1473 km^2 (18% of the total area). Crete is one of the most important agricultural and touristic islands of the Mediterranean region (Fig. 1A). In Crete, as well as in many other islands in the Mediterranean, the main water supply is groundwater, while agriculture and touristic activities have become more intensive leading to water scarcity or/and low groundwater quality (Kourgialas and Karatzas, 2014a). Based on the above and taking into consideration that the Mediterranean islands are very vulnerable to climate change, the introduction of a groundwater footprint index which incorporates both the quantity and quality components is a challenge that needs to be addressed in order to design and implement effective, efficient, and inclusive water policies.

The island of Crete contains sub-regions that are characterized by complex geological structure consisting of limestones, impermeable formations and flysch formations (Water Resources Department of the Prefecture of Crete, 2014). The base layer consists of limestones of the Crete-Mani series, impermeable Phyllite-Quartzite series and formations of the Tripolis and Pindos zone (limestones and flysch), neogene deposits (such as marls and limestones) and Quaternary clastic sediments (Parleros et al., 2004). The major aquifers occur within the carbonate rocks (karstic aquifers) of the Crete-Mani series and the Tripolis zone, which cover about 40% of the total area of the island. In many parts of the island, the karstic aquifer systems discharge groundwater through springs. The island of Crete is characterized by 11 main aquifer systems, 76 springs and 19 main river systems as shown in Fig. 1(A) and (B). Five of these aquifer systems are Neogenic and six are karstic, each having a unique hydrogeological behavior. In Crete, the majority of rivers are temporary and the flow mainly derives from spring discharge. (Water Resources Department of the Prefecture of Crete, 2014; Kourgialas and Karatzas, 2014a).