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Blue water scarcity in the Black Sea catchment: Identifying key actors in the water-ecosystem-energy-food nexus

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ABSTRACT

Large-scale water scarcity indicators have been widely used to map and inform decision makers and the public about the use of river flows, a vital and limited renewable resource. However, spatiotemporal interrelations among users and administrative entities are still lacking in most large-scale studies. Water scarcity and interrelations are at the core of the water-ecosystem-energy-food nexus. In this paper, we balance water availability in the Black Sea catchment with requirements and consumptive use of key water users, i.e., municipalities, power plants, manufacturing, irrigation and livestock breeding, accounting for evaporation from major reservoirs as well as environmental flow requirements. We use graph theory to highlight interrelations between users and countries along the hydrological network. The results show that water scarcity occurs mainly in the summer due to higher demand for irrigation and reservoir evaporation in conjunction with relatively lower water resources, and in the fall-winter period due to lower water resources and the relatively high demand for preserving ecosystems and from sectors other than irrigation. Cooling power plants and the demands of urban areas cause scarcity in many isolated locations in the winter and, to a far greater spatial extent, in the summer with the demands for irrigation. Interrelations in water scarcity-prone areas are mainly between relatively small, intra-national rivers, for which the underlying national and regional governments act as key players in mitigating water scarcity within the catchment. However, many interrelations exist for larger rivers, highlighting the need for international cooperation that could be achieved through a water-ecosystem-energy-food nexus.

1. Introduction

Water scarcity is a growing concern in many parts of the world as it leads to conflicts, overexploitation of aquifers, increased pollution, alteration of ecosystems, and various negative effects on human health, food and goods production, and economic well-being (Jury and Vaux, 2007; Kummu et al., 2010).

Water scarcity is both a natural and anthropogenic phenomenon (Jaeger et al., 2013). It can be caused not only by unfavorable climate changes and the failure of a society to adapt but also by excessive and increasing water demand vital to sustaining population growth, industry and agriculture. Moreover, water infrastructure can change the temporal pattern of streamflow, and human activities that consume water through evaporation or incorporation into products eventually deplete a significant amount of resources from the hydrological system (Hoekstra et al., 2012).

There has been a growing recognition that ecosystems are a central and legally established water user, and in 1982, the World Charter for Nature imposed further reductions to water use in nation states committed to their protection. Consequently, competition for available resources is likely to increase (FAO, 2012). This raises the need to decrease water demand, improve the efficiency of water consumption, and lessen the impacts of consumptive use and streamflow regulations to ensure a balance between socioeconomic development and environmental protection (Hamdy et al., 2003).

At the Bonn 2011 Nexus Conference, the concept of a water nexus, which allows for causal links between users and their common resources in water management plans (Hoff, 2011), was

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identified as an innovative way to mitigate water scarcity. The purpose of this approach is to encourage cooperation, reduce trade-offs, and improve consumption efficiency and cross-sectorial policy coherence so that undesirable effects from water use or climate change can be reduced (Bazilian et al., 2011). To this aim, evaluating nexus structures and dynamics in a geographical area allows for the prediction of potential conflicts or opportunities for synergy among users (Wolf, 2007).

The Black Sea catchment suffers from water scarcity in many areas and is subject to a complex set of interrelations involving 23 countries, many different types of users, and four important international river basins. The need for improving ecological conditions and managing growing conflicts of interest in the area (GIWA, 2011) requires regional coordination by the existing national and international institutional framework, including the Black Sea Commission and the International Commission for the Protection of the Danube River (Myroshnychenko et al., 2015). Indeed, water scarcity can be a trigger for cooperation among countries instead of a source of conflict, primarily in situations where institutional frameworks exist (Gizelis and Wooden, 2010) and if scarcity is not extreme, but moderate (Dinar, 2009).

A few global and regional studies have assessed water availability, use and scarcity in the catchment (Baer et al., 2015; Floerke et al., 2012; Hoekstra et al., 2012; Karabulut et al., 2015; Lehmann et al., 2015). Although some of these reports localize users, none have examined upstream-downstream interrelations in detail.

Interrelations are at the core of the nexus concept. In this paper, we identify interrelations along the hydrological network using graph theory (Gould, 2012). We focus on so-called surface "blue water" (Falkenmark and Rockstrom, 2006) that is available in rivers.

We intend to answer the following questions:

- Where and when is water scarcity most likely to occur in the Black Sea catchment?
- What countries and users are involved in these water scarce areas and what are their upstream-downstream interrelations?
- How can such analysis be employed in a nexus framework to mitigate water scarcity in the Black Sea catchment?

To answer these questions, we spatiotemporally balanced water availability with environmental flow requirements, as well as water withdrawals and consumptive use by the main types of water users, specifically municipalities, energy, manufacturing, irrigation, and livestock breeding while taking into account evaporation from major reservoirs. Then, we identify existing upstream-downstream interrelations among countries and types of users using a directed acyclic graph (DAG) (Gould, 2012) of the river network. The users and countries identified as key players should be given priority to mitigate water scarcity in the catchment by implementing a nexus regulatory framework.

2. Methods

2.1. Study area

The Black Sea catchment is situated in the Northern hemisphere at the interface between Europe and western Asia. It covers an area of approximately 2.4 million km^2 and includes four important transboundary river basins: the Danube, the Dnieper, the Dniester, and the Don (Fig. 1).

The catchment is home to a large variety of topographic and climatic conditions ranging from temperate and alpine areas in the west, continental and steppe regions in the north and the east, and Mediterranean and semi-arid areas in the south.

As a transnational entity, the catchment covers parts of 23 countries[1], and is inhabited by more than 180 million people (UNEP, 2013; World Bank, 2015). Municipalities, industries, and agriculture are all major water users, depending on region (FAO, 2013), and ecosystems preservation has been legally recognized in all countries (Paleari et al., 2005).

The catchment is subject to various international water treaties and policies. The major international agreements are established by the Black Sea Commission (BSC) in the coastal states, the International Commission for the Protection of the Danube River (ICPDR) in the Danube river basin, and the Water Framework Directive (WFD) in the European Union and candidate countries (Paleari et al., 2005).

The catchment was the focus of European research project enviroGRIDS (Lehmann et al., 2015) between the years 2009 and 2013, which aimed at building the capacity for this region to use and share earth observation data to support sustainable development (Giuliani et al., 2013). The present work builds on the outcomes of this project, primarily the hydrological model for the entire Black Sea catchment realized at sub-basin and daily temporal resolution (Rouholahnejad et al., 2014).

2.2. Frameworks of analysis

This work was accomplished in several consecutive steps, linked as in Fig. 2. (1) First, we assessed river flows (RF) with the Soil and Water Assessment Tool (SWAT) (Rouholahnejad et al., 2014). (2) Then, we estimated water withdrawals (WW) and consumptive use (WC) for municipalities, power plants, manufacturing, irrigation, and livestock breeding. (3) Adding WC to RF, we estimated the naturalized river flow (NRF). NRF is then used to assess environmental flow requirements (EFR), i.e., the part of flow necessary for preserving critical ecosystem structures and functions. The remaining NRF after allocation of EFR is the quantity of water available (WA) for human use without harming the environment. (4) We then allocate water consumptive use (WC), i.e., the evaporation or incorporation into products of human activities. Next, we compare water withdrawals (WW) of human activities with the remaining available water to identify sub-basins and periods of water scarcity through water scarcity indices (WSI). (5) We identify upstream-downstream interrelations among users and countries using surface water as an entry point for defining nexus structures in the Black Sea catchment on the ground as it is a common resource to all users.

We subdivided the Black Sea catchment into the 23 national territories mentioned previously, nine main river basins[2] and 12,982 sub-basins of $\geq$100 km^2, the latter having been defined by hydrological modeling (Rouholahnejad et al., 2014). These sub-basins were the smallest units of analysis and were subsequently aggregated into river basins, national territories, or catchments when required (Fig. 3).

As water availability and requirements vary widely throughout the year, we used a monthly time scale to take into account these variations.

2.3. Water availability

Rouholahnejad et al. (2014) modeled blue and green water availability with the Soil and Water Assessment Tool (SWAT)

[1] Albania, Austria, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Georgia, Germany, Hungary, Italia, Macedonia, Moldova, Montenegro, Poland, Romania, Russia, Serbia (incl. Kosovo), Slovakia, Slovenia, Switzerland, Turkey, Ukraine

[2] Danube, Dnieper, Dniester, Don, Kelkit, Kizil, Kuban, Rioni, Southern Bug