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Ecohydrology and hydrogeological processes: groundwater–ecosystem interactions with special emphasis on abiotic processes

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ABSTRACT

This paper presents a review on the integration of hydrological, ecological and hydrogeological processes into Integrated Water Resources Management (IWRM) practice. These processes, for example, interact and take part in the process of creation of groundwater-related wetlands, which are an important part of the Earth's biodiversity. Tools for integrating water and ecosystems are presented, with emphasis on the hydrogeological aspects as often they are poorly considered. Recent pioneering projects (IGCP-604, UNESCO-IHP, GENESIS, and Groundwater Governance) developed models for the future integration of ecosystem health with groundwater exploitation. An IWRM approach where groundwater-related wetlands and the groundwater systems upon which they depend are included in conjunctive water management decisions can be an accepted and workable paradigm that will benefit present and future generations.

1. Introduction and background

Ecohydrology (EH) is conceived as a transdisciplinary paradigm, to deal with water-related problems in order to support sustainable development (Zalewski, 2015). There are several international projects that, since 2000, have developed this theme: Water Programme for Environmental Sustainability (WPA II, 2006–2009), European projects (GENESIS and INTERFACES) and GEF Projects, e.g. managing lakes and their basins for sustainable use (ILEC, 2005), IGCP-604, UNESCO-IHP, GWG-2014, among others. This concept is related to Hydroecology (HE) which has been defined by Dunbar and Acreman (2001) as "the linkage of the knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales". But EH and HE are different disciplines, concepts and ways of thinking, largely explained by Zalewski (2015). According to this author, the most important differences between EH and HE are in methodology, nevertheless as expressed by Petts (2007): "Ecology has created an environment of opportunity to embed hydrogeological perspectives within water

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resources management". This definition implies not just a comprehensive approach of the hydrological processes involved in the water cycle in its three dimensions, but also a real understanding of the quantitative and qualitative aspects of such processes in order to create a conceptual model, basic platform to later generate a hydrological model able to simulate future water management scenarios.

In many parts of the world, groundwater is extensively exploited due to its temporal and spatial accessibility, which is also crucial for many ecosystems, thus jeopardizing base flows and ecosystem sustainability due to competition.

Wetland behaviour is linked to groundwater and surface flow functioning, and to land use in the catchment. Thus, the protection of wetlands and of their services to human wellbeing is most effective when coordinated with other management programmes such as water and land management. Moreover, wetlands performance is controlled by factors that occur at different temporal and space scales and which maintain a hierarchical spatial organization: large scale factors are influenced by geographical, geological, climatic, economic and political aspects that do not act or are barely noticed at the local scale. The concept and consideration of what is currently called Integrated Water Resources Management (IWRM) addresses multifaceted water resources both from the technical and the governance points of view (Martínez-Santos et al., 2014). This should consider the existence of wetlands and the services they provide, by carefully managing the available water resources, both natural (surface water, groundwater, imported water from other areas, rainfall harvesting, etc.) and industrial or artificial (seawater and brackish water desalination, water reclamation), and even the consideration of virtual water (hidden flow of water if food or other commodities are traded from one place to another) (UNEP-MAP UNESCO-IHP, 2011).

IWRM was defined by the Global Water Partnership (GWP) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic social welfare in an equitable manner without compromising the sustainability of vital ecosystems". IWRM, expressed through the conjunctive use of surface and groundwater, is a paradigm that incorporates technical, scientific, political, legislative, social and organizational aspects of a water system (Molina et al., 2009). Nevertheless and according to Zalewski (2015), to achieve sustainability, society needs to optimize water resources use instead of maximizing the benefits they can provide. In recent decades, an increase in the withdrawal of groundwater, mainly for human consumption and irrigation, has led to a reduction in its accessibility in many parts of the world with important consequences for aquatic environments (Acreman, 2000; Custodio, 2001, 2002; Llamas and Custodio, 2004; Vrba, 2004; Sophocleous, 2004). Some aquifers are not replenished at the time scale of human, society and ecosystem behaviour (GENESIS Project), i.e. their exploitation is not sustainable in terms of a steady state water balance. Pumping from aquifers readjusts the hydrological balance under natural conditions with consequences on the relationships between its different components. Groundwater withdrawal leads to a reduction of natural aquifer discharge and under some circumstances increases recharge, which may affect the functioning of the natural environment (Dumont, 2015). When groundwater is pumped from an aquifer, the "groundwater head topography" is modified, creating drawdown. Once the perturbation reaches an area of interaction between the groundwater and land topographies or a groundwater divide, the rates of inflows into and outflows from the aquifer change (based on Theis, 1940). These changes may be observed in (a) areas of discharge, through flow or evapotranspiration, a lower groundwater table generates a decrease in the discharge rate, e.g., flows to springs and rivers decline or phreatophytes are no longer able to reach the groundwater table (Fig. 1), and (b) in areas of rejected recharge where the water table used to be close to the ground surface. Pumping results in an increase in recharge rate and less surface water flows are generated. The Upper Guadiana basin is a wellknown example of this phenomenon (Llamas, 1988; Martínez-Cortina et al., 2011; Martínez-Santos and Martínez-Alfaro, 2010; Martínez-Santos et al., 2008).

Therefore, the aim of this paper is to characterize the hydrogeological processes occurring in the interaction between groundwater and wetlands within the framework of Integrated Water Resources Management (IWRM).

2. Groundwater related wetlands and IWRM

While hydrologists, hydrogeologists and ecologists move forward on understanding the complex relationships between water and ecosystems, there are still many open questions, in particular concerning the relationship between groundwater and groundwater-related wetlands (GRW).

Although IWRM is a mature and widely used concept, this does not imply that it does not need review and update, as shown in Table 1.

Under an enlightened IWRM approach, the balance of positive and negative impacts associated with the intensive use of groundwater should be assessed as part of an integrated system, making it possible to formulate management scenarios on the basis of previously established goals and objectives. To achieve this goal, two complementary approaches are needed for both a scientific study and consequently a correct management framework: basin scale and wetland-bed scale. Both approaches are not new and have been largely explained by several authors (Sophocleous, 2002, 2004; Plan Andaluz de Humedales, 2002; Kløve et al., 2013). This corresponds to the fact that the key processes to maintain the ecological integrity of wetlands occur at two levels.

Dumont (2015) provides a detailed description of alterations from withdrawals of water in a watershed. It mainly shows that pumping generates, on the one hand, aquifer stock consumption and, on the other hand, an increase in recharge and decrease in discharge, i.e. disruption of discharge to surface water bodies and ecosystems, with varying proportions through time. Therefore, the criteria used for decisions must reflect all