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Research papers

Combining COSMO-SkyMed satellites data and numerical modeling for the dynamic management of artificial recharge basins

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ABSTRACT

Many urbanized areas in the world are using artificial recharge basins (ARB) as an efficient solution to maintain adequate groundwater recharge while coping with flooding problems. The effective management of these basins to adequately maintain their functionality over mid-to-long term requires a suitable monitoring network. Here, we explored the use of a temporal satellite analysis to closely evaluate the efficiency of the ARB in terms of infiltration capacity, depending on hydraulic conditions of the topsoil transitioning from unclogged to clogged conditions in the ARB.

COSMO-SkyMed synthetic aperture radar (SAR) images were integrated with ground data and numerical modeling to advance the capability for monitoring low water levels and flooded areas within the ARB. The understanding of biofilm development and effects was achieved by identifying anomalous drawdown phases, by constraining ponding boundary conditions in the numerical model, and by estimating subsequent infiltration rate changes under progressive clogging.

With appropriate meteorological conditions (consecutive rainfall events separated by few dry days), the biofilm could develop rapidly and cover large surfaces (e.g., 22 ha) in about two months. During this process, the hydraulic conductivity of the basin surface could decrease by more than three orders of magnitude, completely altering the relationship with the local groundwater regime. Quantitative estimation of the evolution of the infiltration rate provides crucial insights about the overall recharge behavior of ARBs to make reliable economical plans in both the design and monitoring phase.

1. Introduction

Artificial recharge basins (ARBs) are hydraulic engineering facilities adopted for a variety of purposes, including managed aquifer recharge (MAR) (e.g. Martin, 2013). ARBs work by diverting surficial water intentionally into the basins, to tackle water shortage problems (Buhyain, 2015). Moreover, ARBs are used to reduce storm water floors, while forcing part of surficial water to infiltrate into the subsurface through the ARBs topsoil (Kattan et al., 2010).

The correct use of ARBs requires an adequate and frequent monitoring of water levels within the ARBs. This effort can be complicated by several factors. For instance, the installation of in-situ instrumentation can be costly and difficult, and the data reading may be susceptible to failures resulting in incomplete records (e.g. Masetti et al., 2016). Moreover, the irregular geometry of the surface may let water accumulate preferentially in some parts of the ARBs, leaving other areas partially inundated or even completely empty. Such irregularity of the ground surface was observed during a field campaign in July 2015 (Masetti et al., 2015) on a large ARB located in the Po Plain in northern Italy, an area frequently subject to flooding due to the extensive urbanization. Given that it is virtually impossible to install water level sensors in all possible portions within the ARB, manual measurements of water levels within the ARB would be needed, resulting in potentially high operational costs for ARB monitoring.

Another complication is the clogging formation, such as biofilm on the ARB bottom surface, which sporadically masks the ground surface. The biofilm cover may lead to differential infiltration of water in specific sectors of the ARB (e.g. Pedretti et al., 2012a) or to an extensive

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impermeable surface across the entire ARB (Martin, 2013). This process is rather common in all managed aquifer recharge facilities (Racz et al., 2012) and plays a crucial role in maintenance cost-and system performance (Houle et al., 2013).

Optical and microwave remote sensing techniques have already been successfully used to observe terrestrial water with applications related to river discharges and runoffs (Brakenridge et al., 2005; Brakenridge et al., 2007), groundwater recharge (Khalaf and Donoghue, 2012; Coelho et al., 2017), wetlands, (Nghiem et al., 2017), global health (United Nations, 2017), flood hazards (DFO, Dartmouth Flood Observatory, 2016), water resources management (Alsdorf et al., 2007; Nghiem et al., 2012), and snow cover (Pettinato et al., 2013; Pettinato and Santi, 2014). For MAR involving infiltration basins, applications are scarce. Pedretti et al. (2011, 2012b) showed that satellite photographic images could be combined to ground measurements from double-ring infiltrometers to quantify the infiltration capacity of the ARBs ground surface before and after flooding events generating clogging. While this approach is a useful and promising tool to improve the design and management of these facilities, it was tested on a static pilot ARB area in absence of flooding water. However, operational ARBs are dynamic systems with a short time scale of flooding-emptying basin cycles (Masetti et al., 2016). In this case, an extensive series of images collected at high resolutions in time and in space over the same area are required to study the dynamic variability of flooding events in the basins. The problem of satellite optical images is that they are significantly affected by clouds and floating vegetation on the water surface (Fig. 1, inset in the right panel), which could partially or completely limit their use to monitor the water covered area in the basin (Ran and Lu, 2012). Moreover, water turbidity and suspended sediments may further complicate the spectral characteristics for water remote sensing.

Active microwave sensors, such as synthetic aperture radar (SAR), are very effective tools to detect the presence of water in various landscape conditions including open surfaces, vegetated agricultural lands, and urban areas, regardless of cloud cover and absence of solar illumination (Paloscia et al., 2008; Paloscia and Santi, 2012). Compared to other land surface types, water surface typically has very low radar backscatter, especially at large incidence angles, showing different polarization signatures depending on wind speed and wind direction (Grieco et al., 2015; Li and Lehner, 2014; Nghiem et al., 1997, 2004). This important property can be used to identify inland water bodies from other surface targets. Various applications of SAR in hydrological studies have been reported in the literature (e.g., Santoro and Wegmüller, 2014; Bartsch et al., 2012; Hostache et al., 2009; Pulvirenti et al., 2014; Xie et al., 2016). Details on the methods used to infer information about water presence on soil surface and land use classification from satellite images, including threshold and change detection methods or unsupervised and semi-automated solutions, have been reported elsewhere (e.g., Santoro and Wegmüller, 2014; Pradhan et al., 2016; Pulvirenti et al., 2014; Paloscia et al., 2008; Paloscia and Santi, 2012; Pettinato et al., 2013; Pettinato and Santi, 2014).

This paper presents a novel framework, which combines SAR-based observations from the COSMO-SkyMed (CSK) satellites and numerical modeling, to support the management of large-scale ARBs by monitoring and predicting the dynamic change in ARB hydraulic behavior. The CSK system is a space-borne, four-satellite constellation, which is fully operational since 2011. CSK satellites are equipped with SAR sensors that operate at X-band in sun-synchronous orbits (Coletta et al., 2008; Grimani et al., 2016). The CSK SAR constellation enables much more frequent revisits to a specific location compared to the SAR coverage from a single-satellite mission. Different applications on the use of CSK for detecting waterline changes in intertidal area (Ding et al., 2015), and flooding areas boundaries in urban and agricultural areas (Pulvirenti et al., 2016; Boni et al., 2016) were published.

The goal of this analysis is to evaluate the capability of CSK SARs as a quantitative tool to support decision-making processes regarding MAR activities using ARBs. As a case study, we focus on the Po Plain ARB, where continuous measurements of local rainfall and aquifer head and a calibrated and validated numerical flow model are available to obtain quantitative estimates of transient changes in hydraulic properties of the ARB during the MAR activities (Masetti et al., 2016). Using these data and tools, our specific objectives are: (1) to explore any link between remote sensing information from CSK satellites and existing ground measurement from the targeted ARB to assess the impact on the local aquifer recharge, and (2) to explore the use of transient satellite analysis to evaluate the efficiency of the ARB in terms of topsoil infiltration capacity, particularly on the hydraulic conditions of the topsoil transitioning from unclogged to clogged conditions in the ARB.

In addressing the above goals, we explicitly note that the originality of the results to be presented in this paper includes: (1) use of the temporal dimension with frequent revisit by taking advantage of the CSK system as a constellation of SARs allowing the capability to resolve the short time scale involved in the hydrogeological processes occurred in the ARB, (2) establishing the relationship between satellite SAR observations with the ARB hydrological processes by using a composite of in-situ and surface observations together with modeling results, and

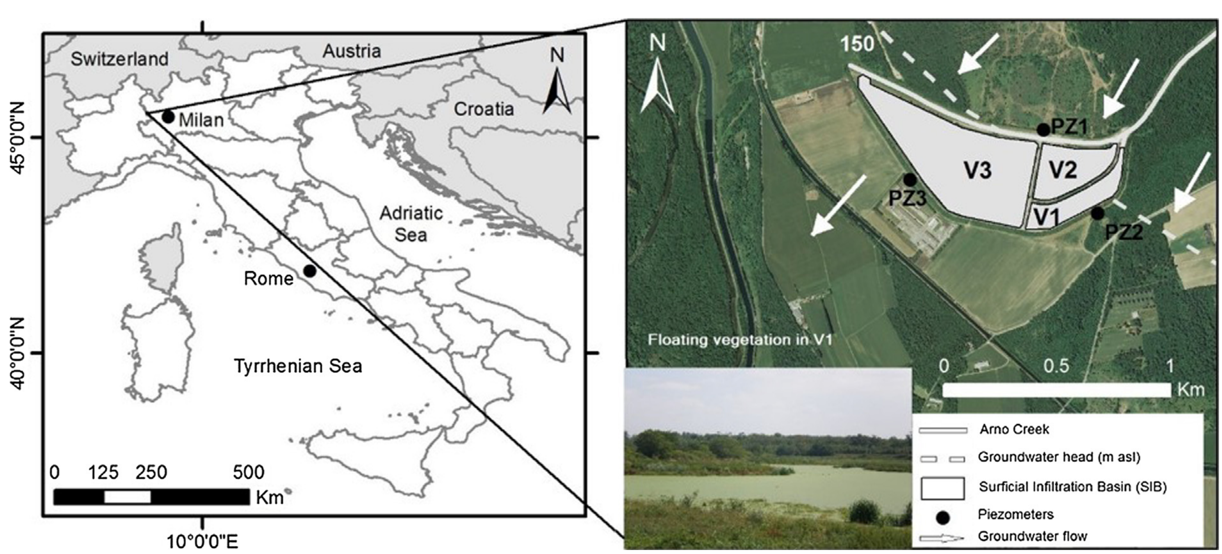

Fig. 1. Location of the study area and detail of the sub-basins composing the superficial infiltration basin, the inset photograph shows the floating vegetation on the water surface. Hydrogeological sketch of the area with the position of the basin (bottom panel) (adapted from Masetti et al., 2016).