Journal of Contaminant Hydrology 192 (2016) 87–100

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

The nitrogen cycle in highly urbanized tropical regions and the effect of river–aquifer interactions: The case of Jakarta and the Ciliwung River

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form 13 June 2016
Accepted 20 June 2016
Available online 02 July 2016

Keywords:
Nitrogen pollution
Groundwater contamination
River–groundwater interactions
Coupled model
Jakarta

ABSTRACT

Groundwater is extensively used in Jakarta to compensate for the limited public water supply network. Recent observations show a rise in nitrate (NO_3^-) levels in the shallow aquifer, thus pointing at a potential risk for public health. The detected levels are still below national and international regulatory limits for drinking water but a strategy is necessary to contain the growing problem. We combine 3 years of available data in the Ciliwung River, the major river flowing through Jakarta, with a distributed river–aquifer interaction model to characterise the impact of urbanisation on the N-cycle of both surface and groundwater systems. Results show that the N-cycle in the river–aquifer system is heterogeneous in space, seasonal dependent (i.e. flow regime) and strongly affected by urban pollution. Results suggest also that although the main sources of N related groundwater pollution are leaking septic tanks, the aquifer interaction with the Ciliwung River may locally have a strong effect on the concentrations. In the general context of pollution control in urban areas, this study demonstrates how advanced process-based models can be efficiently used in combination with field measurements to bring new insights into complex contamination problems. These are essential for more effective and integrated management of water quality in river–aquifer systems.

1. Introduction

Nitrate (NO_3^-) is one of the most common pollutants of groundwater in the world. When combined with other environmental agents at high concentrations in drinking water, such as aromatic amines and arsine, NO_3^- is known to contribute to excessive levels of methemoglobin in the blood of infants (i.e. methemaglobinemia or “baby blue syndrome”) (Fewtrell, 2004), which can lead to delirium, seizures, coma and death in extreme cases (Denshaw-Burke et al., 2015).

A number of studies conducted in Southeast Asian cities like Manila, Bangkok and Jakarta, have pointed at the rising problem of NO_3^- contamination in developing megacities (e.g. (Zhang et al., 2015; Umezawa et al., 2009), which is expected to aggravate in the future with the growing population.

Jakarta is a particularly challenging case because of the high population dependency on groundwater for drinking water to compensate for the limited municipal water supply network (ADB, 2013) and its vulnerability to flooding and pollution. High levels of contamination, which include NO_3^- and are a potential risk to public health, have been observed in both the

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http://dx.doi.org/10.1016/j.jconhyd.2016.06.004
0169-7722/

surface (e.g. Costa et al., 2014; Sikder et al., 2012) and groundwater (e.g. Umezawa et al., 2009) resources. In the latter study, the authors conducted a GIS-based monitoring campaign in 2009 using a dual isotope approach and concluded that although the concentration of NO_3^- and NH_4^+ (ammonium cation) was still not excessive, it was likely to increase with the rising population.

Moreover, since 1985 the average water table lowered by more than 20 m in Central Jakarta due to overexploitation of the aquifer (Kagabu et al., 2010). This has been linked to intrusion of saline waters in the northern coastal areas and to a higher risk of urban pollution propagating from the shallow aquifer to deeper layers in the groundwater system (Costa et al., 2015b).

In such a complex context, effective rehabilitation and preventive measures to control the growing problem of NO_3^- in groundwater require a comprehensive understanding of the major contamination sources and pathways, as well as of the dominant biochemical processes involved in the N-cycle of the aquatic systems in Jakarta.

It is estimated that 95% of the septic tanks leak (Kerstens et al., 2015) and human waste originating from sewer leakage has been identified as the major direct source of nutrient pollution (Umezawa et al., 2009). However, very little is known about the role that surface waters, which are also highly contaminated and enter the aquifer via infiltration, have in the total groundwater NO_3^- contamination budget. For instance, Irawan et al. (2014) looked at the interactions between the Ciliwung River, the major river flowing through Jakarta, and the shallow aquifer, and concluded that although complex at localized scales and highly variable in space, there was a close relationship between water quality observations in both systems.

In this study we bring new insights into the spatial and seasonal characteristics of the N-cycle in both the surface and groundwater systems of Jakarta by using 3 years of available field observations to setup a newly developed physically-based river–aquifer interaction model. Although numerical simulations of coupled systems are generally computational demanding, studies have shown that the computational price to pay is worth the gain of an unparalleled ability to explore integrated pollution problems (Hibi et al., 2015). In this particular study, the new coupled model is especially used to estimate the contribution of N-pollution infiltration from the Cilliwung River to the observed rise in NO_3^- concentrations in the shallow aquifer. These fluxes are computed for different development scenarios and compared to estimates of leaks from poorly maintained septic tanks in the region to benchmark these two pollution sources.

While the results from this research provide information that is specific to the city of Jakarta, the methodology can be used to support the identification of appropriate management solutions in other regions subject to water quality problems related to river–aquifer pollution exchange.

2. Material and methods

2.1. Regional setting

Jakarta, the capital city of Indonesia, was ranked in 2015 as the world's second largest urban area (Demographia, 2015) and the 10th fastest growing megacity (Forbes, 2015). Fig. 1 shows the Jabodetabek region, which includes the cities of Jakarta, Bogor, Depok, Bekasi, Tangerang and South Tangerang.

The city has grown dramatically in the last decades and currently its urbanized area extends significantly beyond the national capital district, commonly known as DKI Jakarta, reaching the neighbouring cities of Depok and Bogor. According to Forbes (2015), the population in the Jabodetabek area grew by 34.6% between 2000 and 2010, where it was estimated as 26.75 million.

The municipal water supply and sewerage networks cover, respectively, 31% (in 2008, ADB, 2013) and 3% (in 2002, Sukarma and Pollard, 2002) of the population in Jakarta. As a consequence, groundwater abstractions increased by fourteen times since 1950 (Kagabu et al., 2013) and poorly maintained septic tanks became widely used (IndII, 2014; Morris et al., 1994).

Thirteen rivers flow through DKI Jakarta, the Ciliwung being the largest with approximately 130 km in length and a catchment of 390 km^2. The Ciliwung River is extremely polluted (Palupi et al., 1995) with increasing levels of NO_3^-, *BOD* (Costa et al., 2014; Sikder et al., 2012), heavy metals (Kobayashi et al., 2011), and faecal coliforms.

Groundwater generally exfiltrates into the Ciliwung upstream of Depok, which is at the edge of the metropolitan area of Jakarta, but fluxes reverse thereafter (Irawan et al., 2014) with the river potentially becoming a relevant source of groundwater pollution.

The main aquifer system in Jakarta is, on average, composed by an 80 m thick highly permeable shallow unconfined aquifer and a 250 deep confined aquifer composed by sedimentary rocks of low permeability (Fachri et al., 2003). A groundwater potential depression zone in the central area of Jakarta (CJ, in Fig. 1) has been identified (Kagabu et al., 2013), and the quality of the water has deteriorated as a results of saline intrusion (Chaussard et al., 2013) and N contamination (Umezawa et al., 2009).

2.2. N-cycle in aquatic systems and water quality standards

As summarized in Fig. 2, inorganic N occurs in natural waters mainly in the form of NO_3^-, NO_2^- and NH_4^+, chemical species that may transform into one another via (i) nitrification by aerobic bacteria (NH_4^+ to NO_3^-), (ii) denitrification occurring under anoxic conditions (NO_3^- to N_2), (iii) N-fixation by nitrogenases (i.e. enzymes) present in some organisms (N_2 to NH_4^+) and (iv) ammonification resulting from the decomposition of organic N (N-org to NH_4^+).

NO_3^- can enter the groundwater through a number of pathways (Umezawa et al., 2009). It can originate from the infiltration of precipitation containing N-oxides, NO_3^- contaminated river waters and industrial spills. It can also arise from the leaching of nitrous fertilizers, from pipe leaks at gasworks and/or result from nitrification processes when NH_4^+ and dissolved oxygen (DO) concentrations are both high.

Despite not being subject to sorption, NO_3^- can, in turn, be lost through plants and bacteria uptake (thus being transformed into organic forms) or through denitrification in suboxic or anoxic environments.

Regulatory limits to the presence of nitrate-nitrogen (NO_3^-–N) in drinking water are set to 50 mg-NO_3^-–N/l by the World Health Organization (WHO) and the European Union (EU) and