# Impact of a Storm-Water Infiltration Basin on the Recharge Dynamics in a Highly Permeable Aquifer

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**Abstract** Infiltration basins are increasingly used worldwide to both mitigate flood risk in urban areas and artificially recharge shallow aquifers. Understanding recharge dynamics controlling the quantity and quality of infiltrating water is required to correctly design and maintain these facilities. In this paper, we focus on quantitative aspects and analyze in detail the temporal evolution of infiltration rates in basins overlying highly permeable aquifers. In these settings, recharge is a complex process due to high recharge rate and volume, undetected soil hydraulic heterogeneity and topsoil clogging. A 16-ha infiltration basin in Northern Italy has been intensively characterized and monitored for over four years. Field and laboratory tests were performed to characterize soil hydraulic properties. An unsaturated-saturated numerical model was implemented to obtain additional quantitative information supporting experimental data. Results show a strong impact of the infiltration basin on natural recharge patterns. When properly maintained (no clogging of topsoil), estimated infiltration rates from the bottom of the basin are about fifty times higher than recharge under natural conditions in the same area. When the infiltration basin is not properly maintained, bioclogging progressively diminishes the infiltration capacity of the basin, which turns to have no impact on aquifer recharge. Recharge patterns are highly erratic and difficult to predict. We observed natural recharge rates of the order of 1 m/h and a poor correlation between recharge times and maximum intensity of rainfall events. Due to the complex behavior of the recharge, the numerical model (based on the classical Richards equation) is able to explain many but not all the observed recharge events. Macropores flow

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and Lisse effects on piezometric measurements may be responsible for the disagreement between model predictions and observations.

**Keywords** Infiltration basin · Storm water · Uncertainty · Clogging · Lisse effect · Macropores · Heterogeneity · Decision making

## 1 Introduction

Infiltration basins are hydraulic engineering facilities created with the double purpose of mitigating flood risk by storm water and artificially recharging shallow aquifers (e.g. Browne et al. 2008; Manghi et al. 2011; Stafford et al. 2015). A detailed hydrogeological characterization and prediction of the impact of these facilities on local aquifers must be carefully considered (Dechesne et al. 2004).

A number of these facilities are currently active in the Po Plain in Northern Italy. This densely populated area recently suffered from several flooding events prompting the construction of several new infiltration facilities. One limitation is the lack of space in this highly urbanized region. Most basins are located in the proximity of urban settings with drinking water supply wells and concentrations of aquifer contaminants are typically close to regulatory limits. New hydraulic facilities that infiltrate superficial storm water in aquifers could potentially bring additional contaminant loading. Quantitative understanding of basin-driven aquifer recharge, such as recharge time, rates, and volumes, is necessary to accurately estimate mass loading infiltration in the subsurface through these facilities and to plan adequate groundwater monitoring.

At the scale of the catchment and over large time scales, natural recharge can be computed through a variety of methods and models with different level of complexity, including watershed scale models (Yen et al. 2014), entropy-based approaches (Mondal et al. 2012) or reactive modeling approaches (Bobba 2012). However, at the infiltration basin scale and on shorter time scales, recharge is usually quite erratic and a clear identification of the impact of the basin on the local aquifer dynamics is not easily achieved through the above mentioned methods. Indeed a more detailed modeling approach is required to account for the impact of multiple local factors affecting natural and artificial recharge (e.g. Manglik and Rai 2014). In this paper, we focused on two important aspects that seem to render the analysis of the hydrodynamic behavior of these facilities particularly complex.

The first factor is clogging (e.g. Baveye et al. 1998; Guin 1972; Okubo and Matsumoto 1979; Perez-Paricio and Carrera 1999). Clogging refers to the pore occlusion in topsoil (e.g. Kandra et al. 2014) due to a variety of chemical, physical and biological processes that jointly diminish the infiltration capacity of the basin by reducing the topsoils hydraulic conductivity ($K$) over time (Pedretti et al. 2012). Clogging can reduce the average areal recharge from these facilities by several orders of magnitude (e.g. Barahona-Palomo et al. 2010; Langhans et al. 2011). Pitt et al. (1999) outlined how the impact on the quantity and the quality of the underlying aquifer and the progressive clogging of the soil at the infiltration surface are the two main problems associated with infiltration basin.

The second factor is aquifer heterogeneity. The vadose zone of alluvial aquifer can be characterized by preferential recharging paths embedded in a generally less conductive matrix, which generates localized high aquifer recharge rates. These paths, known as 'macropores' (e.g. Beven and Germann 2013), are typically randomly distributed and of difficult detection and characterization in practical applications. As a result, field observations are sometimes at odds with theoretical explanation of phenomena associated with recharge

heterogeneity. The reader is referred to Beven and Germann (2013) for an exhaustive review of these concepts.

We present the results of a hydrogeological study aimed to quantitatively assess the impact of a 16-ha infiltration basin on the recharge dynamics of the underlying unconfined and highly permeable aquifer. Aquifer and infiltration basin hydrogeological parameters, as well as their spatial variation, were characterized by performing field and laboratory tests. Field monitoring and modeling activities were carried out to estimate natural and artificial aquifer recharge volumes and infiltration rates. Groundwater levels and rainfall events were monitored for four years (from 2009 to 2013) allowing to evaluate seasonal effects both under clogged and unclogged conditions of the basin topsoil (being representative of natural and artificial conditions, respectively).

We demonstrate how the strategy developed in the framework of this study, based on combining monitoring and modeling activities, can be used for: (a) providing reliable estimate of aquifer recharge volumes and their changes through time due to the infiltration basin activity, (b) improving groundwater monitoring strategies, by appropriately identifying piezometer locations and sampling times, and (c) better planning for maintenance works in order to sustain the infiltration process throughout the lifetime of the infiltration basins. Moreover we also highlight some future developments that could be integrated in this study to further increase the reliability of numerical models for quantifying aquifer recharge in this environment.

## 2 Site Description

The Lonate-Pozzolo basin (LPB) is one of the most important infiltration basin in Italy. It is located about 40 km west from the city of Milan, in a flat area close to a series of fluvial terraces formed by the Ticino river. The river acts as a gaining stream, resulting in a local groundwater flow with mean direction SW (Fig. 1a).

The study area is characterized by the presence of the highly-permeable Upper Po Plain aquifer, a surficial unconfined aquifer mainly constituted by gravel and sands deposit of fluvial origin. Discontinuous clay layers start from 50 meters below the land surface (Fig. 1b). The mean aquifer transmissivity is typically very high, with a mean hydraulic conductivity ranging from $K=10^{-3}$ m/s to $K=10^{-5}$ m/s and thickness of about 100 m (ENI-AGIP 2002). The depth of the water table (thickness of the vadose zone) ranges between 30 m and 40 m, depending on the regional aquifer recharge conditions and the management of the LPB.

LPB was activated in 2001 with the dual purpose of mitigating the flood risk associated with the nearby 'Torrente Arno' (Arno creek) and providing artificial recharge to the local unconfined aquifer. The final reach of the Arno creek had neither natural nor artificial riverbanks and thus, before the construction of the LPB, its water was flowing towards an open field (todays LPB area), causing frequent floods .

The hydraulic facility is composed of three sub-basins. Two of them receive the water first and allow sedimentation of most of the solids out of the water. The third is the main infiltration sub-basin (the actual LPB), which receives pre-sedimented water from the sedimentation sub-basins. It has a length of about 800 m, a maximum width of about 300 m (Fig. 1a) and a depth between 4 and 5 m. Its maximum capacity ($\Delta S$) is $9 \times 10^5$ m$^3$.

Water storage capacity is expected to also include the amount that can quickly infiltrate into the natural basin topsoil ($I$). Therefore the LPB can potentially receive a total volume of precipitation ($P$) and run-off storm water ($RO$) larger than $9 \times 10^5$ m$^3$, as $P + RO$ can be as large as $\Delta S + I$ without exceeding capacity in ideal preconditions.

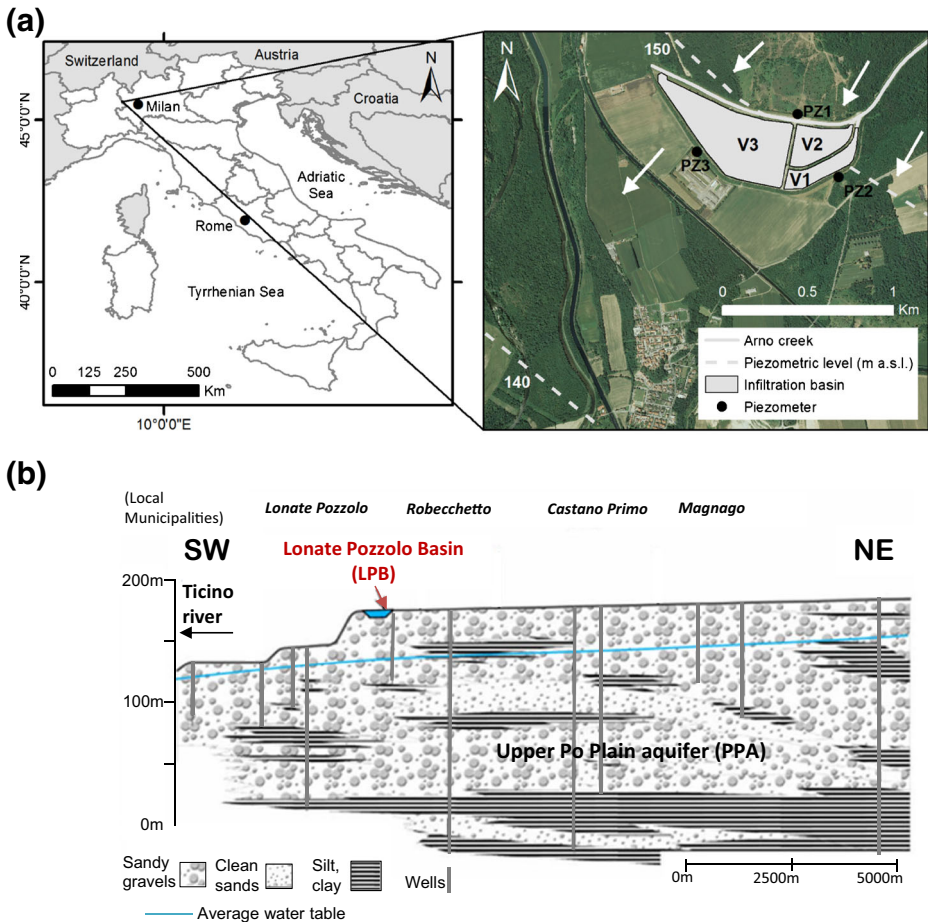**(a)**



**(b)**



**Fig. 1** Geographical position of the LPB from aerial photo (**a**) and schematic hydrogeological sketch of the aquifer below the LPB (**b**). White arrows show the direction of groundwater flow. Coordinates refer to GCS WGS 1984

Evaporation is neglected from these calculations because evaporation rates are expected to be much lower than infiltration rates, provided infiltration basins are properly maintained (e.g. Bouwer 2002).

Since 2001, the average cost for the basin maintenance has been about 600,000 Euros (Interregional Agency for the Po River, personal communication) per year, to comply with the technical and environmental requirements of the Lombardia Region Guidelines (Regione Lombardia 2011). This cost is lower than the expected damage costs caused by potential flooding of urban areas that would occur without the facility.

Due to the brief concentration time of the Arno creek (about 2 hours), storm water enters in the infiltration basin soon after the beginning of rainfall events. On multiple occasions after the construction of the facility, storm-water temporarily covered the entire basin surface.

Owner and Project Team of LPB entered litigation due to the alleged poor effectiveness of the basin to provide both flood control and aquifer recharge. A key question of this litigation was about the effect of the LPB on the recharge rates of the unconfined aquifer. In 2006 (five years after the activation of the LPB) the infiltration sub-basin was completely clogged. Permanent ponding water was covering the entire extension of the facility for long periods, with a slow decrease during dry seasons, mostly by evaporation. During wet seasons, the basin operated as a sort of wetland. Infiltration rates from the bottom of the LPB were greatly reduced and almost stopped. The wetland condition of the LPB caused a legal controversy that ended in 2011. During this time, no survey activities were allowed inside the basin, but only in its close surroundings. The first monitoring activities described in this work started in 2009. In order to restore the original topsoil infiltration capacity, the basin was emptied in summer 2011 and the topsoil was completely renewed with a new gravel bed. In July 2013 (at the end of our experimental observations), the infiltration basin was working properly. Bioclogging was observed only in few localized areas within the basin, without affecting its average infiltration capacity.

## 2.1 Site Characterization and Data Collection

Two piezometers (Pz1 and Pz3) were built in 2009 in the proximity of the LPB (Fig. 1a) to compare aquifer recharge dynamics under natural conditions and when influenced by the presence of the basin.

The piezometers Pz1 and Pz3 were drilled up to a depth of 50 m and are located 60 m and 50 m from the upgradient and downgradient boundary of the infiltration basin, respectively. For both wells, the stratigraphic logs from drilling cores display a mixture of sand and gravel. This suggests a roughly homogeneous high hydraulic conductivity in the shallow aquifer. Soil samples obtained from these cores were analyzed using constant-head permeability tests (ASTM 2006). A saturated hydraulic conductivity $K = 10^{-4}$ m/s was found for samples at a depth of 10 m (i.e. in the vadose zone). Grain size distribution, organic content, soil specific weight and soil-water characteristic curves (SWCC) were also determined from these samples.

Groundwater heads were monitored from 2009 to 2013 at both piezometers. Head levels have been monitored hourly through the study period using a Keller DCX 16 sensor. This monitoring can be divided into two stages. The first, from 2009 to 2011, was during 'clogged' basin conditions before maintenance of the basin, and the second, from 2011 to 2013, was during 'unclogged' basin conditions when the basin was maintained. During the entire monitoring period, rainfall was continuously monitored at a gauge station located about 1 km from the basin.

Due to legal limitations, it was not possible to attend the topsoil maintenance operations in 2011, and thus to characterize the type of soil clogging. Legal documents (unpublished data) indicated that a small amount of fine material was found on the bottom of the basin, without specifying compositional or textural properties of this material. Observations, made after the topsoil maintenance operations, suggested that fine material could have been biofilm. Figure 2 shows the macroscopic and microscopic characteristic of biofilm formed as a consequence of few rainfall events after the topsoil maintenance operations. This biofilm, however, formed only on portions of the basin. Since the basin had been entirely flooded a few times since the maintenance operations in 2011, the localized formation of biofilm can be related to soil-specific biological colonies. Indeed, bioclogging develops at markedly different rates depending on heterogeneous soil textural and compositional properties of the basin topsoil, such as grain size and pore-size distribution, amount of clay
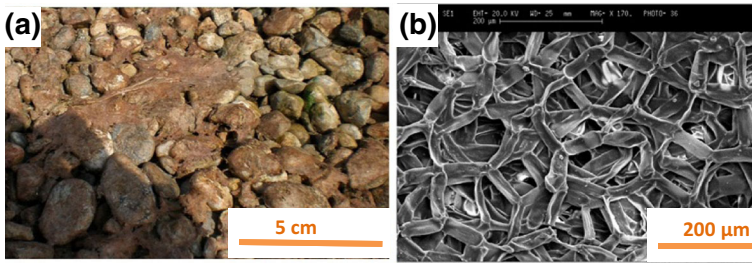
**Fig. 2** Macroscopic (**a**) and microscopic (**b**) images of the biofilm found in the infiltration basin after some rainfall events posterior to the 2011 topsoil maintenance

and/or carbon content (e.g. Baveye et al. 1998; Guin 1972; Perez-Paricio and Carrera 1999; Pedretti et al. 2012).

After the topsoil maintenance operations and until the end of the monitoring period, bioclogging has remained a localized phenomenon, without completely compromising the basin. This was probably caused by extended periods without rainfall, which left most of the basin empty for sufficient time to cause the drying of the biofilm (Fig. 2a) and its natural biodegradation (e.g. Houston et al. 1999). On areas not affected by clogging a few double-ring infiltrometer tests (Smith 1972) showed an average $K = 3 \times 10^{-4}$ m/s. These values were slightly higher than the representative values at 10 m below the land surface and indicated that the original topsoil infiltration capacity was effectively restored and maintained to pre-clogging conditions.

## 3 Recharge Analysis

To assess how recharge occurs in the basin under natural conditions, and to evaluate the impact of basin-driven recharge of aquifer dynamics, we first analyzed the 'recharge time' recorded from the head fluctuations at the piezometer Pz3. This piezometer is hydraulically downgradient (with respect to the basin) and thus potentially affected by the LPB-driven recharge.

Recharge time is estimated as the time elapsed from the beginning of representative precipitation events to the initial response of groundwater levels (head increase). Because of the possible convolution of multiple rainfall events on the resulting groundwater head response, we analyzed only selected, sufficiently clustered events in which rainfall-head responses could be uniquely identified. We calculated the time since the first detected precipitation (hourly records) occurred in these clusters. An example of how recharge time was calculated and of the concept of clustered rainfall is graphically reported in Fig. 3a for five selected events between October and November 2010. The recharge time is shown by horizontal arrows in the x-axis (time).

Using the water-table fluctuation method (Delin et al. 2007; Healy and Cook 2002; Scanlon and Cook 2002), the amount of recharge ($R$) based on the recharge time is defined as

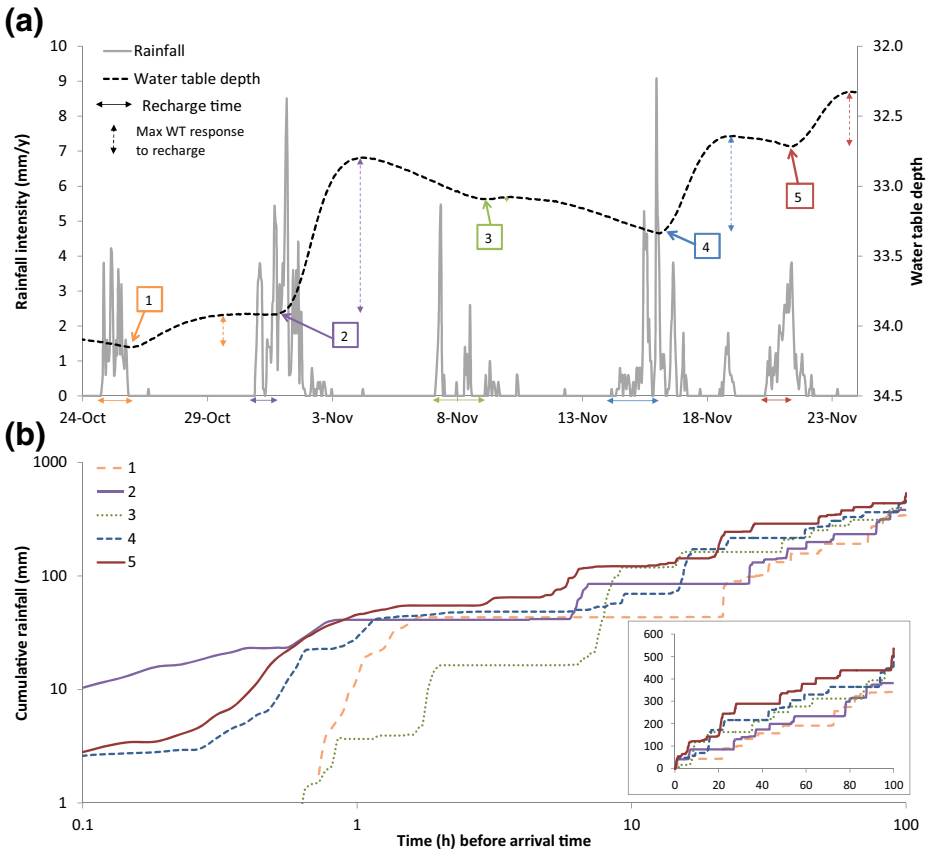$$R = \frac{S_y \Delta h}{\Delta t} \tag{1}$$

**(a)**



**(b)**



**Fig. 3 a** Comparison between rainfall and fluctuation of the water table for five selected clustered rainfall events in the clogged condition; (**b**) Cumulative rainfall before the arrival time for the selected events in (**a**). The inclusion represents the same plot (**b**) in arithmetic scales

where $S_y$ is the specific yield [-], $\Delta h$ is the maximum registered groundwater head change [m] and $\Delta t$ is the time [h] within which the change occurs from the beginning of the rainfall events (i.e. the recharge time). The study area satisfied most of the conditions for the water-table fluctuation method: (a) an unconfined aquifer with sharp water level changes; (b) no pumping and, generally, no anthropogenic activities that could influence the natural groundwater level over short time scales; (c) short time lag for individual rainfall event; and (d) independent knowledge of the yield value of the material composing the aquifers. We estimated the specific yield as $S_y = 0.2$, a value which also corresponds to the mean estimated aquifer porosity.

From Eq. 1, we calculated an Infiltration Ratio ($IR$) as

$$IR = \frac{R\Delta t}{T_r} \tag{2}$$

where $T_r$ is the total amount of rainfall (m) during the event that caused the water table change. The comparison between $IR$ under unclogged and clogged conditions provides an indication of the impact of the infiltration basin on the groundwater system. It should be

noted that one drawback of this method is that $IR$ is expected to increase with the length of rainfall events and there is the need to maximize the potential that all the rainfall volume contributes to the highest measured groundwater head. To reduce these uncertainties, only continuous rainfall events lasting less than 12 hours were considered.

## 3.1 Recharge under Clogged Conditions

Twenty-five representative recharge events were selected to evaluate recharge in the first monitoring stage (i.e. from 2009 to 2011), when the infiltration basin was completely clogged. Recharge time measured during this period can be uniquely associated to natural recharge conditions (Fig. 3).

Assuming that maximum rainfall events could have a predominant impact on recharge dynamics and in particular on recharge time, we first evaluated any possible correlation between recharge times and maximum hourly rainfall intensity within the 25 selected clustered rainfall events (Fig. 4a). Similarly, we compared the relationship between recharge time and groundwater depth at the beginning of each rainfall event (Fig. 4b).

Three main aspects can be highlighted from these results. (1) On average, the graphs seem to illustrate that the recharge time decreases as the maximum rainfall intensity increases, indicating a positive effect of major rainfall events on infiltration velocities. Consistently, infiltration travel time increases as water table depths increase. (2) Scatter is wide; the coefficient of determination based on linear regression is quite low in both plots, emphasizing that infiltration velocities depend on multiple factors and cannot be highly related to a single variable. (3) Very low recharge times were observed, resulting in high infiltration rates, of the order of 1 m/h.

The above observations allow for a preliminary evaluation of natural recharge conditions for this aquifer. First, despite the high thickness of the vadose zone ($>30$ m), the extremely high infiltration rates make the unconfined aquifer highly vulnerable to contamination from the basin. These rates seem to confirm the high hydraulic conductivity of gravel and sand composing the aquifer. Estimated recharge times were based on observations made at one
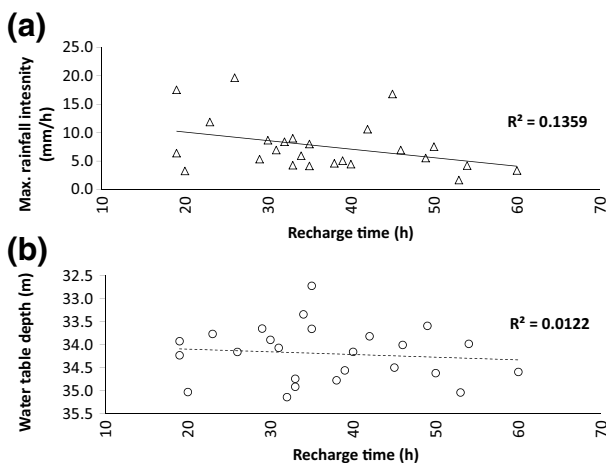


**Fig. 4** Relationship between recharge time and maximum rainfall rate (**a**) and between recharge time and initial groundwater depth (**b**), under clogged basin conditions (natural aquifer recharge). Here, $R^2$ is the coefficient of determination corresponding to the best-fitting linear regression

individual piezometer located downgradient the basin. A few field observations indicated that extremely high recharge values (>1 m/h) could be associated with a quick transmission of pressure pulses immediately after infiltration events and can be measured as local head fluctuations. However, this phenomenon (known as Lisse effect (e.g. Weeks 2002)) should not be very significant when the soil permeability is large and recharge volumes are low (e.g. Guo et al. 2008) as it occurs in the study area when the basin is clogged.

To obtain additional insights on measured aquifer responses to recharge events, we carefully analyzed the selected response events reported in Fig. 3a. We assumed that the vadose zone wetting conditions prior to each of these events were similar, given that they all occurred in the wet season that starts at the end of August or beginning of September. Figure 3a shows that rainfall (gray lines) had a relatively lower impact on the head differences (vertical dotted lines) after events 1 and 3 than after events 4 and 5. This difference cannot be accounted for by the maximum precipitation rates; for instance, maximum rainfall intensities around event 3 (lower head level differences) are larger than around event 5 (higher head differences).

Figure 3b displays the cumulative rainfall at the time of head response. This plot displays some anomalies in estimated recharge patterns. For instance, events 1 and 2 show very similar cumulative rainfall between 1 h and 5 h prior to the recharge event, but their recharge fingerprint (Fig. 3a) is quite different. Moreover, events 3 and 4 have comparable recharge times, but the cumulative rainfall patterns are quite different between the two events.

These observations confirm that recharge under natural hydrological conditions is highly erratic and not easily predictable. The rainfall pattern can have different influence on the infiltration rate and the seepage pattern depends on the hydraulic conductivity of saturated soil, as highlighted for instance by Tsaparas et al. (2002). We can also postulate that the observed complex behavior of recharge at the LPB can be associated with the possible presence of randomly distributed undetected macropores and preferential paths in the vadose zone. These zones can be more or less efficiently activated during the rainfall events and contribute to locally enhance apparent recharge rates. However, the parameterization of macropores-driven recharge remains an unsolved problem in hydrogeology (Beven and Germann 2013).

### 3.2 Recharge under Unclogged Conditions

During the monitoring period following the basin topsoil maintenance operations (2011-2013), the total aquifer recharge may have resulted from the combination of LPB-induced infiltration and natural recharge. A first visual inspection suggests a dramatic impact of the infiltrating basin on the water-table fluctuations, compared to natural recharge patterns (Fig. 5a). A generally more pronounced change in groundwater head under unclogged conditions (max. value 8.61 m) compared to clogged conditions (max. value 0.64 m) is observed. This is also expressed through the difference in IR calculated under clogged and unclogged conditions, which gives a mean IR value of 15 % and 700 %, respectively.

The impact of the LPB on the aquifer recharge is striking and sheds lights on the actual efficiency of these facilities (when properly working and maintained). Despite the use of a relatively simple model, the difference of recharge between the clogged and the unclogged condition is clearly highlighted by the IR estimation. A total of 12 and 6 recharge events, meeting the above mentioned minimum requirements have been used for clogged and unclogged, respectively. Values higher than 100 % clearly indicate the effect of the basin, which acts as a sort of concentrated and augmented recharge area for the unconfined aquifer.
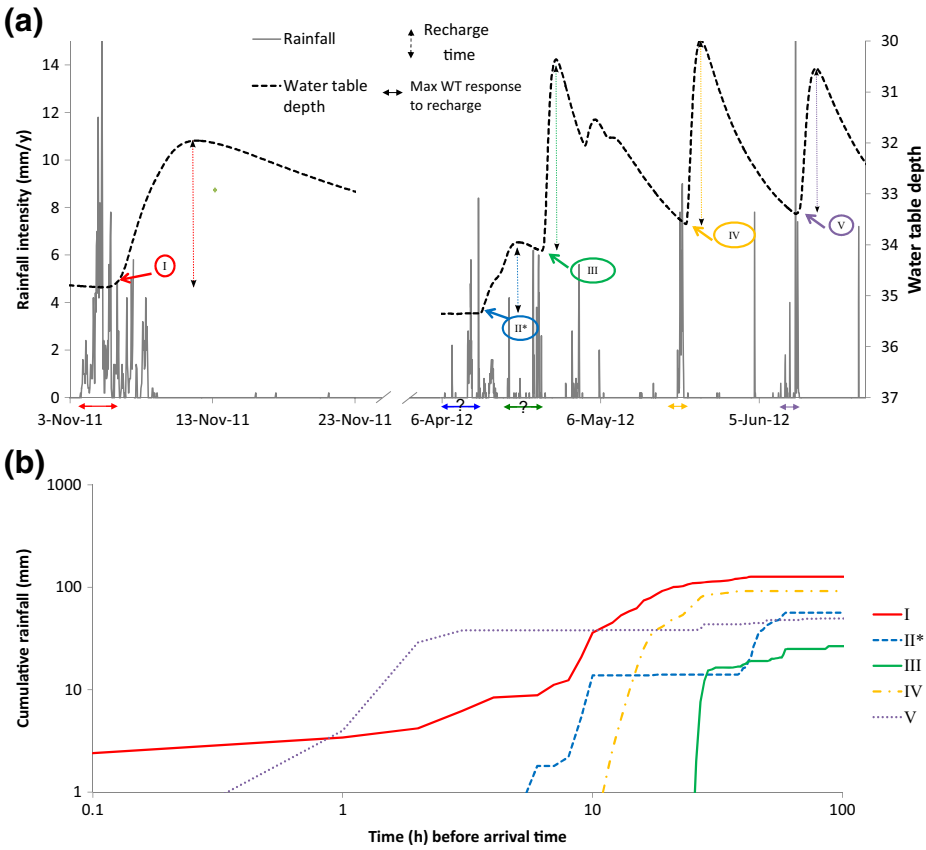
**Fig. 5** (**a**) Comparison between rainfall and fluctuation of the water table for 5 selected clustered rainfall events in the unclogged condition; (**b**) Cumulative rainfall before the arrival time for the selected events in (**a**)

Moreover, the dynamic of groundwater head changes during the infiltration events shows that groundwater quality monitoring should be done from 3 to 5 days after a rainfall events, to catch eventual changes on groundwater quality caused by the infiltration of stored surface water from the infiltration basin. The time interval is site specific and must not be done on a regular time basis but properly evaluated through monitoring and/or modeling.

Figure 5b confirms the erratic nature of aquifer recharge under unclogged conditions. Similarly to the analysis for the clogged conditions, we still observed poor correlation between cumulative rainfall events, maximum head level fluctuations and recharge times. For instance, the head difference for the event with larger cumulative rainfall (I) is smaller than for the event III, which has significantly lower cumulative rainfall. Recharge times seem also uncorrelated with the maximum head changes (e.g. events I and V have comparable total head changes, but different recharge times). This indicates that the basin may have a poor impact on controlling specific recharge dynamics, and does not reduce the uncertainty in predicting individual recharge events.

A quantitative estimation of actual infiltration volumes and rates from the basin at larger time scales is provided in the next section.

# 4 Numerical Modeling

A numerical model has been implemented to obtain a better understanding of the recharge processes locally occurring in the study area. Specifically, we focused on the evaluation of (a) groundwater recharge volumes caused by the LPB activity, (b) the effectiveness of the groundwater monitoring scheme, and (c) the actual ability of a Richards equation based approach to reproduce recharge dynamics in highly transmissive settings.

A finite element code, SEEP/W (GEO-SLOPE 2006) was used for this analysis. This code was successfully tested against several hydrological problems (e.g. Ching-Chuan et al. 2009; Hughes et al. 1998; Kim et al. 2004; Motha and Wigham 1995), including groundwater flow in the vadose zone under superficial ponded and non-ponded conditions (Masetti et al. 2010; Pedretti et al. 2011). The selection of this code was specifically made to simulate unsaturated flow and the boundary condition associated with clogged-unclogged conditions of the topsoil, and to reproduce local head fluctuations measured in the piezometers in the proximity of the domain, which we used to evaluate recharge dynamics associated with the infiltration basin.

## 4.1 Model Setup

The governing flow equation used in SEEP/W is based on the standard Richards equation and is written as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + Q = m_w \gamma_w \frac{\partial h}{\partial t} \tag{3}$$

where $K_x$ and $K_y$ the horizontal and vertical hydraulic conductivity [m/s], respectively (both are a function of the saturation), $Q$ is the applied boundary flux [m³/s], $m_w$ is the slope of the SWCC [-] and $\gamma_w$ is the water specific weight [kN/m³].

The conceptual model (Fig. 6) was composed of a single material (a mix of gravel and sand) with homogeneous isotropic hydraulic conductivity over the entire domain ($K_x = K_y$). The model was developed in 2D as a vertical section connecting the two monitoring piezometers, Pz1 and Pz3; the horizontal Cartesian coordinates are oriented along the regional groundwater flow direction. The bottom of the model was set at a depth of 40 m below the land surface, which is 5 meters below the mean groundwater level. The SWCC has been derived through the method by Gupta and Larson (1979) starting from experimentally measured grain size curve, organic content and specific weight of soils from site material. The hydraulic conductivity - water content ($K - \theta$) function has been obtained from the SWCC and from in situ measured saturated hydraulic conductivity using the criterion by Green and Corey (1971). Evaporation was neglected from the calculations.

The model was used to reproduce infiltration events both under clogged and unclogged conditions. Measured rainfall events and the consequent groundwater level changes measured in the two piezometers were simulated for the two different cases. Head levels at the beginning of each rainfall event were assigned as prescribed head boundary conditions to the 'infinite elements' in the SEEP/W code. This was done to set proper water table levels and recreate observed hydraulic gradients between the two piezometers in the studied domain. Infinite elements similar to classical Cauchy boundary conditions (see GEO-SLOPE (2006) for details). On the top surface, rainfall events were simulated by applying prescribed flux conditions. We used an hourly-based time discretization.

To simulate clogging conditions, we assumed perfectly impermeable basin topsoil, and assigned no-flow boundary condition to the bottom of the infiltration basin (Fig. 6a).
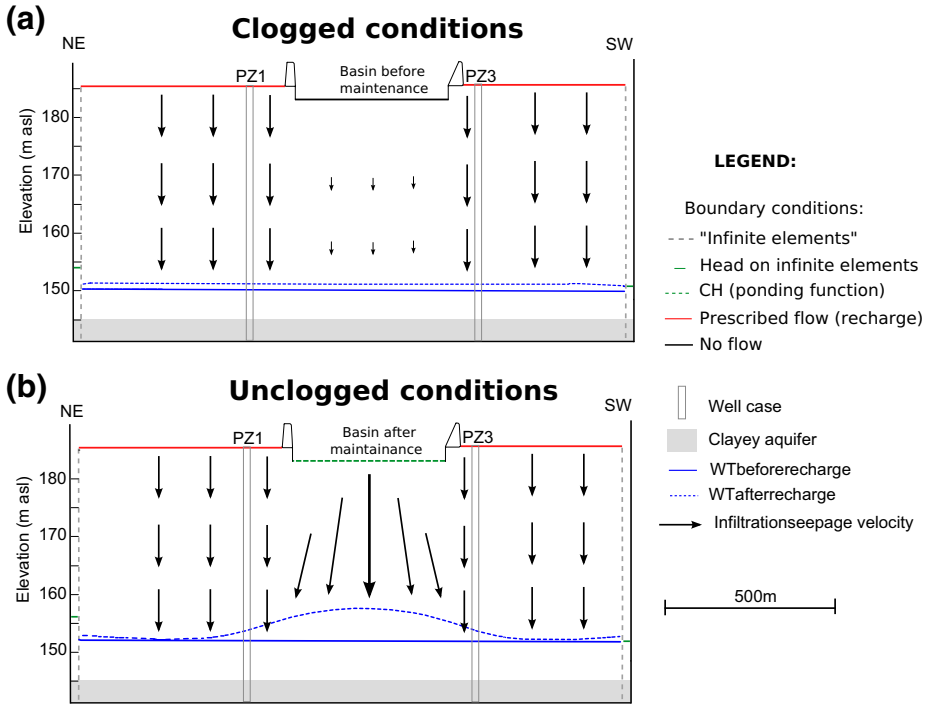
**Fig. 6** Conceptual model and sketch of groundwater level changes (*blue lines*) simulated during a rainfall event in the clogged (**a**) and unclogged (**b**) scenarios. The arrows depict the representative infiltration rate vectors in the different zones of the aquifer depending on the basin topsoil conditions

Unclogged conditions were simulated using transient prescribed head boundary conditions to the bottom of the infiltration basin ('ponding' function) (Fig. 6b). The latter represents the observed water level changes above the unclogged surface.

## 4.2 Model Analysis

Model calibration was performed by comparing calculated and measured groundwater head in a transient regime. We used several of the events discussed in Section 4.1. During calibration only the saturated hydraulic conductivity was changed (and consequently the resulting $K - \theta$ relationship); the SWCC was not calibrated, but based on experimental observations. The calibrated $K$ was found after minimizing the difference between measured and calculated head changes all over the modeled time interval. The resulting optimal value was $K_x = K_y = 2.5 \times 10^{-4}$ m/s, which is very similar to the values directly measured on soil samples, and in line with the average aquifer hydraulic conductivity.

The calibrated model was able to adequately reproduce most of the experimental observations for different rainfall patterns and antecedent moisture conditions (e.g. Morbidelli et al. 2012). Table 1 summarizes the results from a few selected events. Predicted and observed maximum head changes display very low errors (order of $10^{-2}$ m). Larger errors (order of $10^{-1}$ m) were observed for sporadic events. A graphical example of the different quality of model predictions is shown Fig. 7. Possible reasons controlling these larger discrepancies are discussed in the following section. Because of the general low average error, however,

**Table 1** Measured and calculated groundwater changes in some precipitation events under clogged conditions

| Date | Measured GW level increase | Calculated GW level increase | Agreement |
|------|------|------|------|
|  | m | m |  |
| 15-Sep-09 | 0.66 | 0.62 | Good |
| 30-Nov-09 | 0.50 | 0.54 | Good |
| 24-Dec-09 | 0.59 | 0.64 | Good |
| 30-Mar-10 | 0.64 | 0.85 | Overestimated |
| 27-Apr-10 | 0.11 | 0.10 | Good |
| 25-Oct-10 | 0.23 | 0.26 | Good |
| 1-Nov-10 | 1.10 | 1.35 | Overestimated |
| 16-Nov-10 | 0.69 | 0.73 | Good |
| 22-Dec-10 | 0.83 | 0.60 | Underestimated |
| 14-Mar-11 | 0.58 | 0.53 | Good |

the calibrated model is deemed able to adequately provide a quantitative estimation about the aquifer dynamics in the LPB area.

The calibrated model was applied to predict infiltrating volumes below the LPB in unclogged conditions. Recharge volume from the unclogged basin (i.e. uniquely associated to recharge from the basin) is on the order of $10^6$ m$^3$, for single storm-water event, having a return period of few months in the study area. This represents a very high local recharge
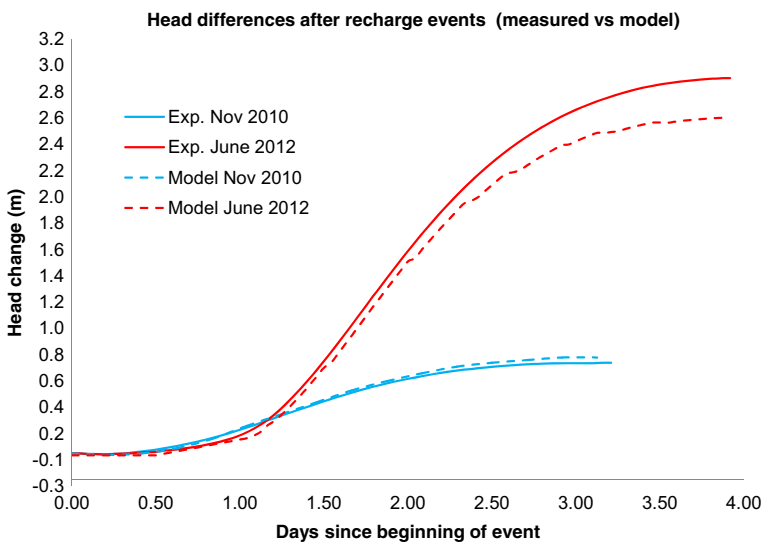


**Fig. 7** Measured and calculated groundwater head changes below the infiltration basin following rainfall events occurred in the clogged (November 2010) and unclogged (June 2012) conditions

amount, which suggests that the artificial recharge from the basin can be highly efficient when the facility is well managed and maintained. These results must focus the attention of administrations and decision makers to other potential problems not analyzed in this work, such as potentially large solute loadings associated with infiltration of urban and storm water collected by the basin.

The numerical results also confirm that the basin-driven recharge significantly influences upgradient head values. The radius of influence of the basin (i.e. the distance at which the impact to basin recharge is no longer appreciated by a change in hydraulic heads) is about 150 m (upgradient from the average direction of the groundwater flow). This value indicates that new monitoring wells should be also located upgradient to the basin in a radius larger than 150 m from the LPB in order to be used as check points to monitor quantitative and qualitative aspects of groundwater not affected by infiltration through the artificial recharge facility.

### 4.3 Discussion: Adequacy of the Modelling Approach

While the model is able to reproduce most of our experimental observations, there are significant discrepancies between model estimations and observations for some specific recharge events, which require attention.

From Table 1, it can be appreciated that the events March 30th 2010 and November 1st 2010 showed a remarkable difference of more than 20 cm between calculated and measured head increase, which may not be easily justified by a mere inadequacy of the model parameterization. Indeed, event November 1st 2010 fell between two events with good calibration and virtually identical moisture conditions. Similar results were obtained using the topsoil-unclogged model; for instance, Fig. 7 shows the transient evolution of head levels in June 2012, where the prediction significantly overestimates the observed trend.

From our experimental dataset and the aquifer characterization, it is not clear what causes such differences. We speculate that the (standard) modeling used in this analysis is able to reproduce most but not all the mechanisms controlling the response of piezometers to recharge events. The SEEP/W model, which is based on classical Richards equation, does not embed recharge mechanisms associated with the activation of preferential paths, e.g. macropores. Following the discussion in Beven and Germann (2013), macropores-driven recharge requires a different modelling approach that can account, for example, nonequilibrium phenomena. We lack quantitative tools and data to test such hypotheses for our case study. In addition, the model cannot reproduce the Lisse effects that could have moderately influenced measured groundwater head fluctuations in piezometers in the unclogged condition, when recharge volume below the infiltration basin are very high. In this condition, pressure pulses can artificially increase groundwater levels inferred from piezometers despite the high hydraulic conductivity of soils composing the unconfined aquifer (Guo et al. 2008; Weeks 2002).

Embedding macropores or Lisse effects in a modeling approach is a challenging task; moreover, strongly supportive data set is required to corroborate the actual validity of these hypotheses. We lack of such information, and thus it was not possible to develop a more complete analysis of the case study. We argue however that a complete understanding of these aspects is of fundamental importance for practical applications. It would further improve model-based estimations that can effectively support decision-makers to correctly design and manage similar artificial infiltration basins, and that the mechanisms controlling recharge dynamics in highly permeable aquifers are correctly identified and can be exported to other similar applications.

## 5 Conclusions

Results from the field monitoring activities and model-based simulations, carried out to assess the recharge dynamics of an unconfined and highly permeable aquifer underlying a 16-ha infiltration basin, show that:

– General recharge dynamics, at the scale of the infiltration basin, can be assessed by a numerical model, based on the classical Richards equation, allowing to explain most of the observed infiltration variability, as a function of both rainfall patterns and antecedent moisture conditions;

– Under clogged conditions, complex natural recharge patterns with estimated infiltration rates of about 1 m/h, mainly uncorrelated with both intensity and cumulative amount of rainfall, were observed;

– Discrepancies between some of the observed and modelled recharge events can be explained by accounting for preferential flow paths (due to presence of macropores) and minor Lisse effects on the water table, both of which cannot be resolved by the numerical model;

– Maintenance of the basin topsoil is the most important aspect to be considered in order to avoid ponding conditions and thus increase the amount of recharge by more than fifty times with respect to natural conditions;

– If the infiltration basin is well maintained, the aquifer recharge increases significantly, along with the potential contaminant loads that can enter the aquifer through the basin;

– The recharge volume associated with a single storm-water event, having a return period of few months in the study area, can be estimated to be roughly $10^6$ m$^3$;

– The radius of influence of the infiltration basin, as estimated from the numerical models, can be of about 150 m off its upgradient boundary;

– Monitoring and modeling activities can be combined to improve groundwater monitoring strategies by identifying the best piezometer locations and sampling times.

**Conflict of Interest** No conflict of interest.

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