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Articles

Potential for groundwater recharge during floods: First-order estimates

Potencial de recarga de acuíferos durante crecidas: estimaciones de primer orden

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Abstract

Observed variations in water levels of aquifers located in arid and semi-arid areas around the world indicate that significant recharge may occur during flooding events that happen with a frequency of one in every decade or so. It is expected that due to climate change there will be more intense floods during the coming decades. Therefore, it is important to improve the current understanding about the recharge that may occur during such extreme events. We perform simple first-order analytical estimates of focused recharge during flood events and use them to calculate potential watershed-scale recharge. We demonstrate that rapid and significant recharge to groundwater during flooding events may occur, being the main recharge mechanisms in hydrological systems located in arid and semi-arid areas. Such potential may have great significance in those regions where groundwater is the main or sole water source. For example, we estimated that the recharge that may occur during a single flood event of a few days duration can be equivalent to more than 30 times the mean annual rainfall recorded in some arid regions. We also show that the time that infiltrated water requires to travel through the vadose zone to reach relatively deep water tables can be less than a few hours under reasonable assumptions.

Keywords: groundwater, floods, arid zones, climate change, soil moisture, aquifers, hydrogeology, water resources, rivers, mathematical models.

Resumen

Observaciones de las variaciones de los niveles de acuíferos ubicados en zonas áridas y semiáridas en distintos países, indican que recarga significativa a los acuíferos puede ocurrir durante inundaciones que suceden en promedio cada década o más. Es probable que como consecuencia del cambio climático ocurran inundaciones más intensas en el futuro. Por lo tanto, es importante aumentar el conocimiento sobre los mecanismos de recarga que pueden sobrevenir durante tales eventos hidrológicos extremos. Presentamos estimaciones de primer orden de la potencial magnitud de la recarga que puede darse durante inundaciones y, extrapolamos esos resultados para calcular el potencial de recarga hacia acuíferos a la escala de cuenca. Demostramos que una rápida y significativa recarga puede producirse durante tales eventos, pudiendo constituir la principal fuente de recarga en acuíferos ubicados en zonas áridas y semiáridas. Ese potencial de recarga puede ser especialmente importante en áreas donde el agua subterránea es la principal o única fuente de agua. Por ejemplo, estimamos que la recarga que podría acaecer durante un solo evento con una duración de pocos días, puede ser equivalente a más de 30 veces la precipitación promedio anual registrada en algunas zonas áridas. También mostramos que el tiempo que el agua que infiltra requiere para alcanzar el nivel freático, incluso en casos en que este se encuentra a profundidad significativa, puede ser menor a algunas horas bajo supuestos realistas.

Palabras clave: agua subterránea, inundación, zona árida, cambio climático, humedad del suelo, capa acuífera, hidrogeología, recursos hídricos, río, modelo matemático.

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Introduction

According to existing records, frequency and magnitude of floods have shown to be especially variable during periods of climate change (Cook *et al*., 1992; Tyler *et al*., 1996; Knox, 2000). For example, chemical analysis of vertical water sample profiles in North Africa indicate that concentrated recharge beneath streams ceased about 5 000 years ago as result of a shift in climate patterns (Scanlon *et al*., 2006). Since the global increase in temperature projected for the coming decades will increase the amount of water vapor in the atmosphere, it is anticipated that this will generate more severe flooding events in many locations around the world (Milly *et al*., 2002; Marchi *et al*., 2010; Whitfield, 2012; Taylor *et al*., 2013). Thus, it is expected that the predicted changes in climate will have direct consequences on groundwater resources through changes in recharge to and discharge from aquifers (Taylor *et al*., 2013; Amanambu *et al*., 2020; Carroll *et al*., 2024). The overall impact of future floods on human and economic activities is difficult to assess due to the complexity of local-scale factors that can increase or mitigate their consequences (Kundzewicz *et al*., 2010; Marchi *et al*., 2010; Ali *et al*., 2017; Brunner *et al*., 2020). Recent flood events in different locations around the world, e.g. Valencia, Spain in November 2024, and Texas, USA in July 2025; have confirmed the potential for the occurrence of very rapid and devastating water level rises in rivers situated in arid or semi-arid regions.

The interaction between surface water and groundwater is a key component of hydrological systems that, among other things, serve to dampen floods and store water in aquifers for future use (Chow *et al*., 1988). Flash floods are rapid (within a few hours) and significant (of the order of up to ten times) increases in flow discharge of natural streams that are usually accompanied by the inundation of large land areas over riverbanks (Ali *et al*., 2017). In semi-arid and arid regions, *i.e.* places where the ratio between annual rainfall to potential evapotranspiration is less than 0.5 (Scanlon *et al*., 2006), aquifer recharge occurs mostly during rare flash flood events, accumulating water in aquifers for its potential use during dry periods (Scanlon *et al*., 2006; Taylor *et al*., 2013; Abbas *et al*., 2020). In the future dry periods may have longer duration, so that demand for groundwater could increase because of its use for irrigation and other economic activities, increasing pressure for the exploitation of groundwater from currently stressed aquifers (Taylor *et al*., 2013).

The direct measurement of exchange fluxes between surface streams and aquifers is difficult, particularly in arid regions where most streams are ephemeral and stay dry during long periods that are interspersed by extreme peak flow events. There are three groups of methods applicable to study the interaction between groundwater and ephemeral streams (Shanafield & Cook, 2014): Streamflow based, groundwater based and infiltration based. The first group is based on measuring differences in streamflow along streams such that transmission losses can be quantified. These types of techniques are difficult to apply in practice during peak flow events because of the lack of calibrated rating curves and the destruction or modification of control sections of gauging stations produced by sediment deposition and/or erosion of the stream bed. The second group consists in estimating infiltration rates from observations of water table changes. This type of method can be used to provide a global estimation of the recharge volume and require only the measurement of water levels in different locations, which is easy to perform in areas with a large number of wells. Finally, techniques based on measuring infiltration include local measurement of surface infiltration

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rates through infiltrometers, monitoring changes in water content through the soil column and/or using natural tracers, e.g. heat or electrical conductivity, for measuring transit times and velocities of the recharged water. The application of these methods can be difficult in areas where the installation of piezometers is problematic, e.g. river bed of streams that may experience large floods. Furthermore, the duration of studies to better understand recharge mechanisms in those regions should cover at least the period between recharge events, which in some cases can be of the order of decades. The combination of those factors can make the management of aquifers more difficult due to the difference between the time scale of the groundwater response and the time frame for human decision making (Bredehoeft *et al*., 1982; Bredehoeft, 2002). Because of the difficulties to directly measure infiltration, it is common to use analytical estimates or numerical simulations to complement observations (e.g. Constantz *et al*., 2002; Twarakavi *et al*., 2008; Brunner *et al*., 2017; Schilling *et al*., 2017; Zhou *et al*., 2018).

Analysis based on field observations and results of numerical simulations have concluded that interaction between surface streams and aquifers can be much stronger during flooding events. For example, Unland *et al*. (2015) concluded that groundwater levels in aquifers connected to streams can increase very rapidly and significantly (up to almost 10 m) during high river stages, and that infiltrated water can travel significant distances away from streams (up to 40 m) within a short time. They also found rapid variations in groundwater flow direction before, during and after flooding events. On the other hand, observations in different regions have shown that recharge to aquifers during extreme events can be enhanced with higher pumping from wells due to the greater storage capacity offered by deeper water tables (Taylor *et al*., 2013; Pino, 2018).

Understanding how more intense floods can impact the interaction between ephemeral surface streams and groundwater can be useful for improving water management and flood mitigation systems (Philipp & Grundmann, 2013; Taylor *et al*., 2013; Jourde *et al*., 2014; Hashemi *et al*., 2015; Brunner *et al*., 2017; El-Saadawy *et al*., 2020; Fathy *et al*., 2021). It can also be relevant to evaluate potential increase in aquifer vulnerability due to intense recharge produced by natural floods or by dam failures during such events (Cenderelli *et al*., 2000; Ascott *et al*., 2016; Youssef *et al*., 2021).

We investigate the interaction between surface water and groundwater during flash flood events from a conceptual point of view. First, we discuss as motivation observations of the response of the groundwater system during a flood event that occurred in the San José River valley in northern Chile. Then, we perform simple first-order estimates of the transit time and potential recharge that may occur during a single flood event of a few days duration. Finally, we make conclusions that are relevant for the assessment of sustainable groundwater exploitation in arid and semi-arid areas.

Motivation: The San José River valley

We consider observations in the San José River valley located in northern Chile near the limit of the driest desert on Earth (Atacama Desert). This watershed located near the border between Peru and Chile (Figure 1), presents many of the problems associated with groundwater management in arid regions discussed above.

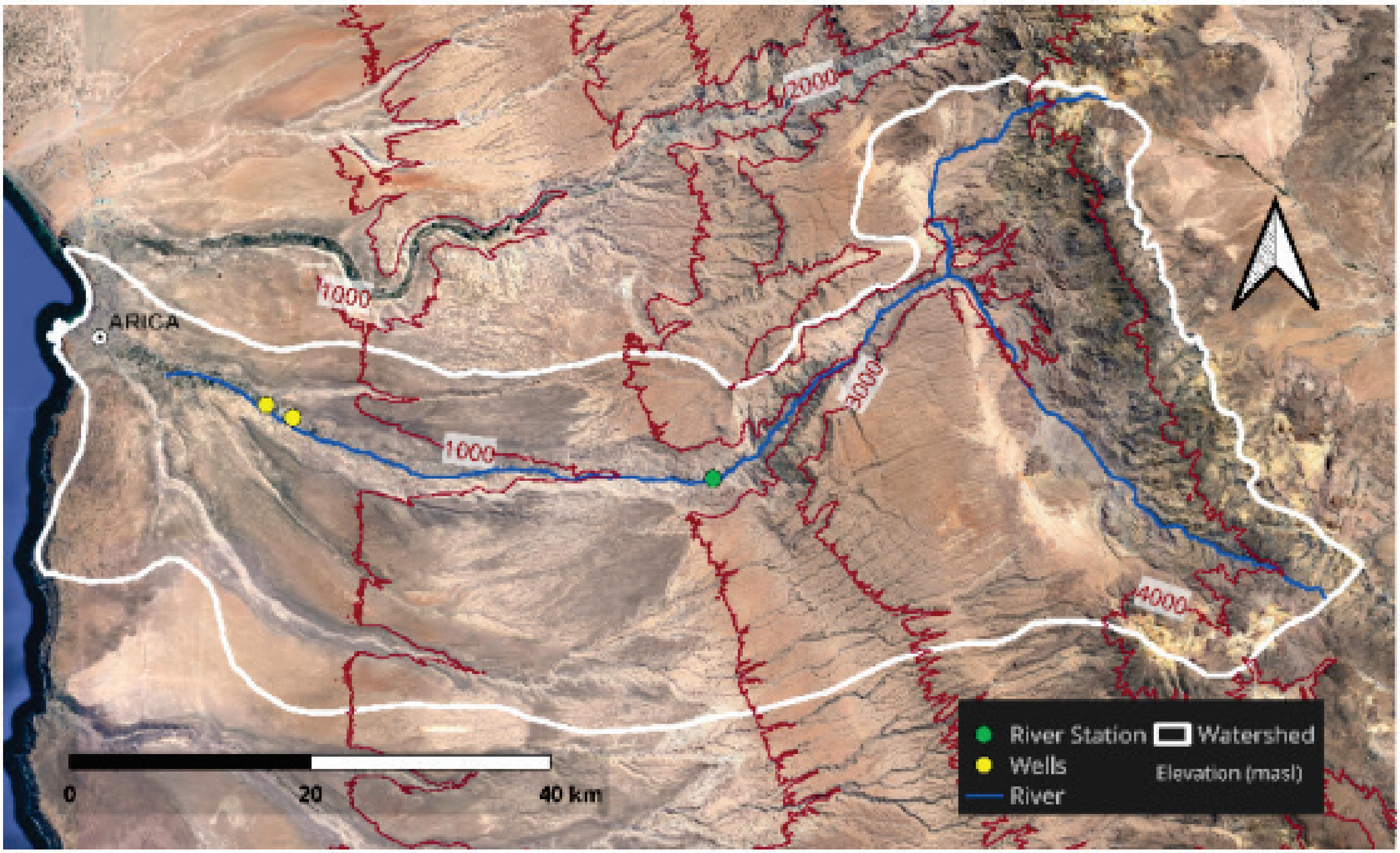

Figure 1. San José River valley in northern Chile. The watershed extends from sea level to more than 4 000 masl. Location of river station (Ausipar, green) and groundwater wells (Las Riveras de Madrid and Pascual Roco, yellow) are approximated. Source: Satellite image from Google Maps (2024).

The watershed covers an area of more than 3 000 km^2 with elevations that range from sea level to more than 5 000 masl near the Andean Mountain Range. The difference in elevation defines four sectors according to precipitation patterns. In the lower part of the basin below 1 000 masl, there is almost no precipitation. For example the mean annual rainfall in the city of Arica is less than 5 mm/year (CR2, 2024). Between 1 000 to 2 000 masl, precipitation is rare; while between that level and 4 500 masl the mean annual rainfall is about 200 mm/year. At higher altitude, precipitation is mainly snow and equivalent to 500 mm/year. Temporal rainfall patterns also show great variability, with periods of several years of limited rainfall interspersed by wet years when rainfall is significantly higher, resulting in flooding events. The flow discharge carried by the San José River is usually low with historical mean daily discharge equal to 1 m^3/s (CR2, 2024), which is channelized through a limited section of the riverbed. However, such configuration changes during flash flood events, when the flow discharge can increase up to ten times and the discharge section can expand considerably because of the inundation of the usually dried flood plain (AC Ingenieros Consultores, 2009; Jiménez, 2013; Pino, 2018).

The aquifer is mainly formed of alluvial deposits and behaves as unconfined. The sediments that compose the main aquifer are permeable sands and gravel with some content or limited layers of less permeable materials like clays and silts (Balic, 2015; Pino, 2018). Figure 2 shows the riverbed in one of the sections of the San José River, which is most of the time covered by a layer of fine sediment deposited during low flow discharge that is removed during peak flow. Thus, during peak flow events there is the potential for direct contact between water in the stream with permeable deposits, usually cobbles, gravels and sands, located at greater depth. The water table depth along the river path fluctuates between ground elevation near springs and swamps, to up to 70 m deep (Jiménez, 2013). The bottom of the aquifer is defined by the elevation of the top of volcanic rocks that are located at variable depth, being at 100 m depth in the lower section near the coast to less than 70 m deep in the upper section (Jiménez, 2013).

Figure 2. The riverbed of the San José River in northern Chile. The riverbed is usually covered by a layer of fine sediments deposited during low discharge, which is remobilized during flash floods. Source: Jiménez (2013).

Tecnología y ciencias del agua, ISSN 2007-2422, 17(5), 404-432. DOI: 10.24850/j-tyca-2026-05-09

The situation described for the San José River valley is representative of other fluvial/alluvial valleys located in arid or semi-arid regions around the world, which are the result of the deposition of materials transported during rare high-energy flood events (Fox & Durnford, 2003).

Due to the fast expansion of agricultural activities in the valley during the last 30 years, there has been an increasing pressure on the use of groundwater resources. In 2008 there were 543 registered groundwater wells, but only 361 were operating. The increasing use of groundwater has produced important drawdowns in groundwater levels over extended periods and reduction in discharge from natural springs, which have been interpreted as an indication that the aquifer is overexploited (AC Ingenieros Consultores, 2009; Jiménez, 2013; Balic, 2015).

Figure 3 shows monthly rainfall and groundwater levels observed in a couple of wells located in the San José River valley. Levels in both wells experienced a rapid recovery of a few meters during and immediately after a flood event that took place in March, 2001. Other wells located nearby experienced similar recovery. That trend is opposite to the constant decline in levels observed in the previous years and since 2002, due to the pumping of groundwater to sustain agricultural activities in the valley. The flood event was the result of concentrated rainfall during a couple of weeks, which resulted in a monthly precipitation that was almost twice the second highest value observed during the 20 years shown in the graph (1990-2010). The rapid recovery of groundwater levels indicate that there was a significant and rapid recharge to the aquifer during that event.

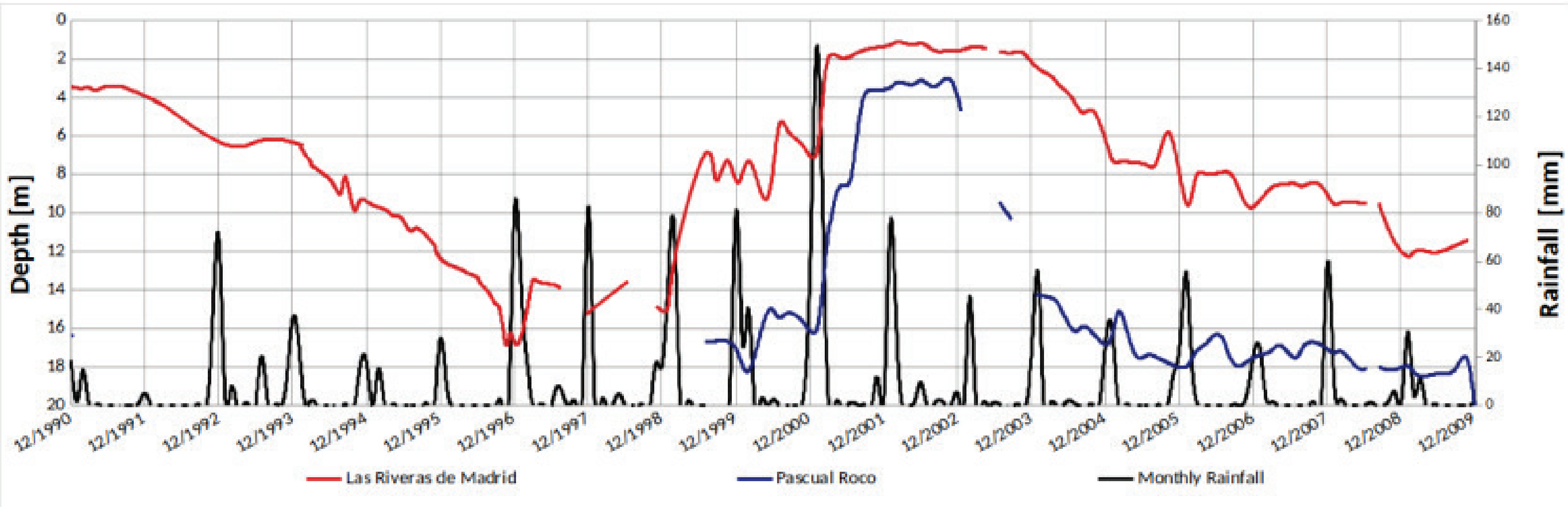

Figure 3. Reported groundwater levels for wells located along the San José River valley, northern Chile. Location of wells is shown in Figure 1. Data from Jiménez (2013).

As in other river basins, measuring flow discharge in the San José River during peak flow is challenging because of the changes in the river morphology and control sections generated by the rapid water level increase. Moreover, it is difficult to calibrate discharge curves for peak flows that happen only on rare occasions (Scanlon *et al*., 2006; AC Ingenieros Consultores, 2009; Brunner *et al*., 2017; Youssef *et al*., 2021). However, available records indicate that daily average peak flow can be up to 40 times greater than the historical average. Instantaneous or hourly peak discharge can be significantly higher, according to some estimations of the order of hundred times higher than the historical average. For example, Figure 4 shows the recorded daily mean hydrograph during the flooding event that took place in March, 2001. For this event, the peak daily discharge exceeded more than forty times the historical average. The main event lasted more than 10 consecutive days and it was followed by a second one of lower magnitude that took place during the next 20 days. The 2001 flood is the largest recorded in the San José River. There are records of only two other events with peak discharge greater than 15 m^3/s for the 52 years period with observations over the range 1967-2019.

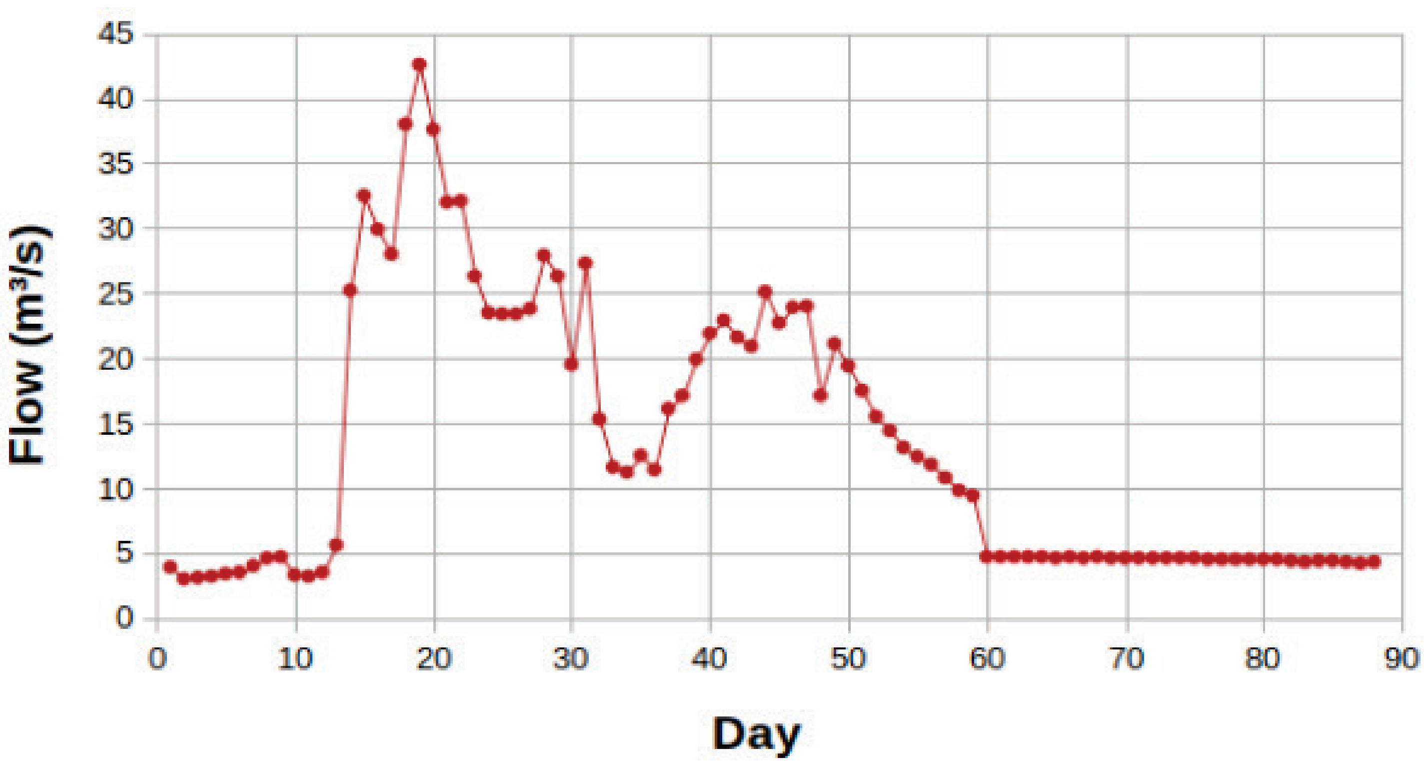

Figure 4. Daily flow discharge recorded at Ausipar station in the San José River valley, northern Chile (CR2, 2024). Graph shows period 01/Feb/2001-30/Apr/2001.

The observations of the groundwater system during the flooding event of March 2001 in the San José River, motivated us to analyze a more general scenario to better understand the dynamics of recharge and the groundwater flow during similar events. For the specific case of the San José River, we refer to a few academic works that have investigated the dynamics of that hydrological system, including the response to the flooding event of 2001: Jiménez (2013), Balic (2015) and Pino (2018).

Methods and results

First-order estimates for potential recharge

For the purpose of the analysis, we consider an idealized system composed of an ephemeral river that during flood events covers a well-defined discharge section and by a subsurface that can be conceptualized as a homogeneous or quasi-homogeneous hydrogeological unit. As an additional simplifying assumption, we assume that the riverbed is dry most of the time and that the main river section carries a significant amount of water only during flood events, during which river stage can be considered constant along the analyzed 2D river section. Hence, we assume that the river system is disconnected from the aquifer most of the time and the water table is relatively deep, which the situation is found in most ephemeral systems located in arid or semi-arid regions.

Neglecting significant mounding of the water table due to low horizontal transmissivity, which is a reasonable assumption for thick permeable or deep water table aquifers (Shanafield *et al*., 2012), infiltration rates can be considered constant during flooding events, except during a short initial period of higher infiltration rates due to the sudden wetting of the dried upper sediments (Philip, 1969). Moreover, since we consider floods with peak discharge that can be ten times higher than the average, we assume that fine sediments deposited during low discharge are removed, so that the effective vertical hydraulic conductivity during those events does not depend on that layer (Brunner *et al*., 2017). Large floods can carry enough water to keep a significant surface water layer above the ground surface, hence the flow problem transitions from one controlled by flow rates to one controlled by a quasi-constant head boundary (Fox & Durnford, 2003). Under those assumptions the flow through the unsaturated zone is quasi-vertical and occurs under unit hydraulic gradient, so that the infiltration rate is equal to the vertical effective hydraulic conductivity (Philip, 1969). Then, we can perform a simple first-order calculation of transit times and infiltration rates assuming that the saturated front beneath the ground surface advances in a piston-like fashion. The assumption of piston-like, *i.e.* the advance of a sharp saturated front, is a good approximation for flow through coarse-grained materials such as sands, in which diffusive flow becomes negligible (Cook *et al*., 1992; Ruifen & Keqin, 2001).

Infiltration rate

Table 1 presents first-order estimates of transit times through the vadose zone and potential recharge rates under the assumptions discussed above. Figures in that table indicate that:

1. There is a potential for very rapid (< 10 h) connection between streams and aquifers during floods events for settings with water table less than 40 m deep. For coarse and medium sand, the time for connection may still be less than 1 day even for deeper water table.
2. Recharge during single flood events that may last a few days can be significant. For example, the estimated potential recharge that could infiltrate in a single day along a 20 m wide 1 km long river section

could provide the amount of water required during 1.3 years by a well that pumps 50 l/s. Since, the total infiltration is linear with the duration of the flood, a few days flood event like the one registered in 2001 in the San José River valley can provide the water to operate wells for several years.

Estimations of transit times through the vadose zone and recharge rates assuming free drainage and piston-like flow, *i.e.* effective vertical infiltration rate $r_v = Kv/\theta$.

Where:

θ = effective porosity.

Kv = effective vertical saturated hydraulic conductivity.

Values of material properties from (Domenico & Schwartz, 1997), Cape Cod (Portniaguine & Solomon, 1998) and Borden (Mackay *et al*., 1986). Last column lists infiltrated volume expressed as time of operation for a well pumping 50 l/s.

Table 1. Estimations of transit times through the vadose zone and recharge rates assuming free drainage and piston-like flow.

Material	Hydraulic conductivity (m/d)	Effective porosity (-)	Vertical infiltration rate (m/d)	Water table depth (m)				Infiltration per kilometer per day (m³)	Equivalent pumping well (Q = 50 l/s) (year)
				20†	40†	60†	80†		
Gravel	2592	0.30	8640	0.1	0.1	0.2	0.2	5.2E+07	32.9
Coarse sand	52	0.35	148	3.2	6.5	9.7	13.0	1.0E+06	0.7
Medium sand	43	0.40	108	4.4	8.9	13.3	17.8	8.6E+05	0.5
Fine sand	17	0.45	38	12.5	25.0	37.5	50.0	3.5E+05	0.2
Cape Cod, sand	100	0.25	400	1.2	2.4	3.6	4.8	2.0E+06	1.3
Borden Site, sand	7	0.30	23	20.6	41.1	61.7	82.3	1.4E+05	0.1
Sandstone	1	0.05	10	46.3	92.6	138.9	185.2	1.0E+04	0.0
Permeable basalt	17	0.05	346	1.4	2.8	4.2	5.6	3.5E+05	0.2
Weathered granite	4	0.50	9	55.6	111.1	166.7	222.2	8.6E+04	0.1
Fractured igneous and metamorphic	26	0.05	518	0.9	1.9	2.8	3.7	5.2E+05	0.3

†transit time in hours for different water table depths (20 to 80).

The estimates presented in Table 1 are based on several assumptions, which may not be valid in practice. However, they provide a good first-order quantification of variables of interest. For example, they assume homogeneity of the subsurface materials that is rarely found in real sites, where effective vertical permeability is controlled by layers of less permeable materials. Nevertheless, for a sandy aquifer one can expect that the effective permeability will be in the range of medium to fine sands materials (Woodbury & Sudicky, 1991; Neuman, 1994; Renard & De Marsily, 1997; Sakata, 2015).

Infiltration volume

Table 2 presents estimates for the potential total infiltration volume in a 20 m wide and 40 km long river section assuming flooding events of different duration. For comparison purposes, the table also includes potential recharge as a percentage of the estimated available storage volume in the San José River valley, equal to approximately 1 400 million cubic meters (1.4 x 109 m^3). For sandy aquifers, these calculations indicate that a significant recharge equivalent to more than 10 % of the available storage volume may occur during a flooding event with a duration of four days.

Table 2. Estimates of total recharge during flood events of different duration (1 to 4 days) assuming a 20 m wide and 40 km long river section. Available storage volume estimated for the San José River valley (1.4 x 109 m^3).

Material	Flood duration (day)*				Flood duration (day)+			
	1	2	3	4	1	2	3	4
Gravel	2074	4147	6221	8294	152 %	304 %	455 %	607 %
Coarse sand	41	83	124	166	3 %	6 %	9 %	12 %
Medium sand	35	69	104	138	3 %	5 %	8 %	10 %
Fine sand	14	28	41	55	1 %	2 %	3 %	4 %
Cape Cod, sand	80	160	240	320	6 %	12 %	18 %	23 %
Borden Site, sand	6	11	17	22	0 %	1 %	1 %	2 %
Sandstone	0	1	1	2	0 %	0 %	0 %	0 %
Permeable basalt	14	28	41	55	1 %	2 %	3 %	4 %
Weathered granite	3	7	10	14	0 %	1 %	1 %	1 %
Fractured igneous and metamorphic	21	41	62	83	2 %	3 %	5 %	6 %

*Total volume in million cubic meters.

+Percentage.

Conclusions

We performed first-order estimates based on piston-flow theory that confirm that there is potential for significant recharge to aquifers during flooding events that may last a few days. Under natural conditions a few of such events that may occur in a time span of a few decades or centuries can potentially explain the stored water in aquifers located in arid and semi-arid regions. In the case of aquifers under exploitation, such events can provide enough water to sustain the operation of wells during a significant period, neglecting potential operational barriers due to large local drawdown around pumping wells (Bredehoeft *et al*., 1982; Bredehoeft, 2002).

Although the analysis is limited to simplified assumptions, the results derived from it may be valid for many systems located in arid and semi-arid areas that present similar conditions in terms of flood frequency, water table depth and type of sediments between the riverbed and the water table.

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Declaration of conflicts of interest

The authors declare that they have no conflicts of interest.

Declaration of AI use

No AI tools were used in the conduct of this study.

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