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Impact of Urban Growth and High Residential Irrigation on Streamflow and Groundwater Levels in a Peri-Urban Semiarid Catchment

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Research Impact Statement: Significant urban recharge associated with irrigation and pipe leaks affects groundwater levels and increases median and low flows in an urban stream in a semiarid peri-urban catchment.

ABSTRACT: The impact of urbanization on groundwater is not simple to understand, as it depends on a variety of factors such as climate, hydrogeology, water management practices, and infrastructure. In semiarid landscapes, the urbanization processes can involve high water consumptions and irrigation increases, which in turn may contribute to groundwater recharge. We assessed the hydrological impacts of urbanization and irrigation rates in an Andean peri-urban catchment located in Chile, in a semiarid climate. For this purpose, we built and validated a coupled surface–groundwater model that allows the verification of a strong stream–aquifer interaction in areas with shallow groundwater, higher than some sewers and portions of the stream. Moreover, we also identified a significant local recharge associated with pipe leaks and inefficient urban irrigation. From the evaluation of different future scenarios, we found a sustainable water conservation scenario will decrease the current groundwater levels, while the median flow reduces from 408 to 389 L/s, and the low flow ($Q_{95\%}$) from 43 to 22 L/s. Overall, our results show the relevance of integrating the modeling of surface and subsurface water resources at different spatial and temporal scales, when assessing the effect of urban development and the suitability of urban water practices.

(KEYWORDS: residential irrigation; peri-urban growth; urban groundwater; Andean catchments; groundwater recharge.)

INTRODUCTION

Currently, more than half of the human population lives in urban areas; this proportion is expected to increase to 66% in the next 30 years (UN 2014). This development has changed land uses tremendously and led to a series of water resource problems (Xiao et al. 2007; Barlow et al. 2012; Whittemore 2012), as well as the emergence of peri-urban catchments (i.e.,

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catchments characterized by a high level of heterogeneity in which natural, rural, and urban areas are mixed (Santo Domingo et al. 2010)). These catchments are especially vulnerable to environmental changes, and their landscape and the connectivity of surface and subsurface flowpaths are likely to be significantly modified (Lee and Heaney 2003; Shuster et al. 2005; Braud et al. 2013).

The impact of urban development on groundwater is by no means simple and easy to understand. Furthermore, this impact is relevant, as it may affect the baseflow in urban streams and rivers (Paul and Meyer 2001; Rose and Peters 2001; Burns et al. 2005; Schoonover et al. 2006; Lan-Anh et al. 2012; Bhaskar et al. 2016a). Commonly, it is recognized that urbanization decreases groundwater recharge due to higher imperviousness (Foster et al. 1994; Hutchinson and Woodside 2002; WMO 2008; Waldron and Larsen 2015). However, the effect of urbanization on groundwater systems is not always very clear, as it depends on the geological and hydrogeological setting, and the adopted stormwater management practices. Accordingly, these characteristics need to be properly investigated at a catchment scale, prior to the development and deployment of any water management strategy (Barron et al. 2013). Aquifers with shallow water tables can have an unexpected response, and can be strongly influenced by urban density and the rate of local groundwater abstraction (Barron et al. 2013). Moreover, human alterations such as deep groundwater supply and septic systems can change the expected effects of human development on groundwater recharge and runoff (Bhaskar et al. 2016b). Burns et al. (2005) showed that the baseflow during a dry period was the largest in a high-density residential catchment, presumably due to discharge of septic effluents through the shallow groundwater system into the stream. Sharp et al. (2009) showed that spring flows are augmented by urban recharge, and thus flow discharge is higher for a given precipitation pattern than prior to urbanization. Several studies report an increase in groundwater recharge as urban development introduces new sources of recharge, such as leaks from storm sewers and irrigation return flows from lawns, parks, and golf courses (e.g., Foster and Chilton 2004; Garcia-Fresca and Sharp 2005; Sharp 2010; Passarello et al. 2012). Garcia-Fresca and Sharp (2005) and Sharp (2010) compiled groundwater recharge values in natural and urbanized locations, which were estimated based on an annual water balance. In most cases, the recharge in urbanized areas increases as compared to natural conditions. Moreover, this increase is larger in more arid zones and cities that may not be able to maintain their infrastructures in the long term (Sharp 2010). Similarly, Foster and Chilton (2004) reported larger rises in groundwater recharge due to urbanization in semiarid catchments.

Modeling groundwater recharge in peri-urban and rural systems is challenging because of the uncertainties related to indirect and localized recharge (Garcia-Fresca and Sharp 2005). Bhaskar et al. (2016b) concluded that an integrated water-cycle-management approach has the best potential to estimate baseflows in heterogeneous landscapes, and that any adaptive management framework for groundwater in urban areas hinges on the establishment of numerical groundwater models and the creation of groundwater and streamflow observation systems.

There are many different numerical models to quantify changes in the water cycle due to land use modifications and the introduction of artificial recharges. Many of the hydrological models integrating surface and subsurface processes simplify the representation of the root zone and the groundwater flows, by using conceptual elements such as reservoirs (Singh and Woolhiser 2002). These elements have a certain storage capacity and contribute to the direct runoff and baseflow of the main catchment. Examples of models using such approximation are VIC (Westerling et al. 2011), SWAT (Dixon and Earls 2012), and SWMM (Rossman 2009; Gironás et al. 2010) in urban settings. On the other hand, when only the groundwater zone is modeled with no integration with surface hydrology, the recharge must be estimated separately, including lateral recharge, direct infiltration from precipitation, infiltration associated with urban irrigation and sewers, and infiltration coming from the riverbed. Usually, all these components come from the independent application of a surface hydrological model not linked to the groundwater model. Hence, interaction and feedback mechanisms between the systems are not accounted for in most of the cases. Because the alteration of the water cycle in urban and peri-urban catchments is related to complex and dynamic phenomena, a dynamic integration of hydrological and groundwater models is essential, particularly in areas where the river–aquifer dynamics affect the riverbed sections, or where sewers are located below the groundwater level (i.e., they can function as drains in drying periods). Good examples of integrated surface–subsurface models are URBS–MODFLOW (Le Delliou et al. 2009), MIKE 11–MODFLOW (Graham et al. 2006), SWAT–MODFLOW (Kim et al. 2008), SWMM–MODFLOW (Yergeau 2010), and WEAP–MODFLOW (Droubi et al. 2008; Hadded et al. 2013). URBS, MIKE 11, and SWMM coupled with MODFLOW were applied in urban settings, with the aim to model one-dimensional channel flow for dynamic hydraulic problems. To our knowledge, such couplings were not applied to hydrological processes involved in peri-urban and natural environments located in a piedmont area. Droubi et al. (2008) and Hadded et al. (2013) applied a coupled WEAP–MODFLOW model to propose best management practices at a subcatchment scale, but they did not study urban and groundwater dynamics, and their links with river–aquifer interactions. Therefore, the study of urban and periurban catchments located in high piedmont areas, with significant surface–groundwater interactions, and a high rate of irrigation in green areas, remains a largely unexplored field of research.

The main objective of this study is to quantify the impacts of urban development on groundwater dynamics in peri-urban catchments located in piedmont regions. The focus is not on the impacts of urbanization on peak flows commonly studied elsewhere, but on the effects on groundwater dynamics and its contribution to baseflow. To represent the recharge and river–aquifer interactions considering the main physical processes in the most realistic way, we implemented a coupled hydrological–hydrogeological numerical model, which was evaluated using flow discharges and groundwater table observations. The three main scientific questions addressed are: (1) how to represent efficiently coupled surface–groundwater interactions in peri-urban settings (2) what is the effect of pipe leaks and high urban irrigation rates (i.e., urban recharge) on groundwater dynamics and (3) what could be the impact of a reduction in this recharge on groundwater levels? Although the case study area is a peri-urban catchment in the piedmont of Santiago, Chile, the methodology here proposed can be generalized to other peri-urban catchments with strong surface–groundwater interactions, heavily dependent on recharge from high mountains and high urban irrigation rates. The structure of this paper is as follows. We first present the study area and available data. Then, we describe the integration of the surface and subsurface models (i.e., WEAP and MODFLOW), with a focus on the domain representation, the coupling, and the calibration and validation strategy. Additionally, we propose scenarios to quantify the effects of urban growth and high urban irrigation rates on the aquifer and baseflow. Subsequently, we show the results and the corresponding discussion, and finally, the main conclusions and perspectives for future research.

STUDY AREA: SANTIAGO'S PIEDMONT

General Description

The study area is the Estero Las Hualtatas River basin and the La Dehesa aquifer, both located in the northern part of the Andean piedmont of Santiago, Chile (Figure 1a,b). This area has a semiarid Mediterranean climate, with 430 mm of average annual precipitation, 28 rainy days per year, and 13°C of average annual temperature (Hernández et al. 2016). The Andean piedmont corresponds to the location where the Andean mountains and the alluvial plain interact, which is characterized by the presence of a group of river courses and sedimentary cones (Romero and Vásquez 2005; Álvarez 2008; Hernández et al. 2016). The vegetation of the piedmont belongs to the ecological region of the high Andean steppe (high zone) and the sclerophyllous forest and shrub (low zone), although there are large areas without any development of native vegetation (Hernández et al. 2016). The soils vary with elevation, with poorly developed soils above abundant rocky outcrops. Recently, the city of Santiago has experienced a significant expansion toward the Andean piedmont sector (Romero et al. 1999, 2010; Romero and Vásquez 2005; Pavez et al. 2010), with a special growth of the peri-urban zones (Banzhaf et al. 2013). In particular, 7,600 ha of the piedmont located along the east part of city between 800 and 1,000 m above sea level (m a.s.l.) is currently under development (Figure 1c). Note that 1,000 m a.s.l. corresponds to the regulated maximum elevation for urban development in the area. This ongoing development has resulted in the introduction and increase of vegetation in public and private areas (De la Barrera et al. 2016). Overall, peri-urban catchments in the Andean piedmont are characterized by a combination of mountainous areas, covered by natural or degraded vegetation, and urban zones, covered by grass and introduced species that require intensive irrigation.

Estero Las Hualtatas Catchment

The Estero Las Hualtatas catchment drains an area of 136 km^2 with elevations from 785 to 2,882 m a.s.l. In its higher portion, there is a high mountain climate, with lower temperatures and snow precipitation. The basin is one of the tributaries of the Mapocho River, which in turn drains to the Maipo River, the outlet of which is in the Pacific Ocean (Figure 1b). The potential urban growth within the catchment is located between 785 and 1,000 m a.s.l., and can cover an area of ~3,200 ha excluding protected zones such as Del Medio Peak (Figure 1d). By 2015, 84% of this area (~2,700 ha) was urbanized, and its boundary tends to match the aquifer boundary (Figure 1d). As for the entire piedmont area in Santiago, the urban vegetation cover is clearly different to that of the nonurbanized area (Figure 1e,f). The Estero

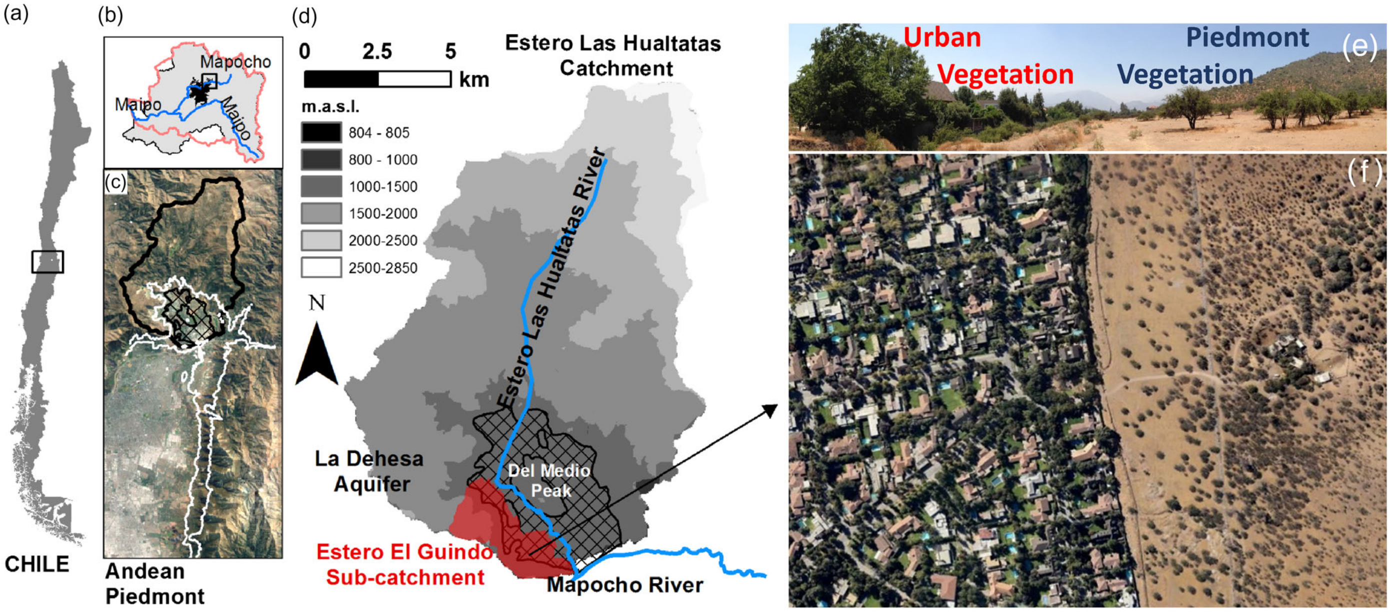

FIGURE 1. Study area. (a) Metropolitan region, Santiago (Chile) in the black box; (b) the Maipo basin (red boundary) and the city of Santiago (black); (c) Andean piedmont located between the 800 and 1,000 m a.s.l. elevation contours, and the Estero Las Hualtatas catchment; (d) details of the Estero Las Hualtatas catchment, La Dehesa aquifer (grid), and Estero El Guindo subcatchment (red); (e, f) profile and plant view of the urban/natural interface showing abundant vegetation in the urban land use and Andean piedmont vegetation (degraded shrub) in the natural land use.

Las Hualtatas catchment is composed of nine subcatchments (Figure 2a): Estero El Guindo, Quebrada Manquehue, Quebrada El Carrizo, Quebrada Oscura, Estero Las Hualtatas, Quebrada Oreganillo, Quebrada El Manzano, Quebrada El Peumo, and Quebrada Gabino. In particular, the streamflow in Estero El Guindo subcatchment (area of 6.5 km^2) was monitored at three locations referred to as Initial, Intermediate, and Outlet Points (Figure 2b), due to the interactions between the flow regime and the aquifer

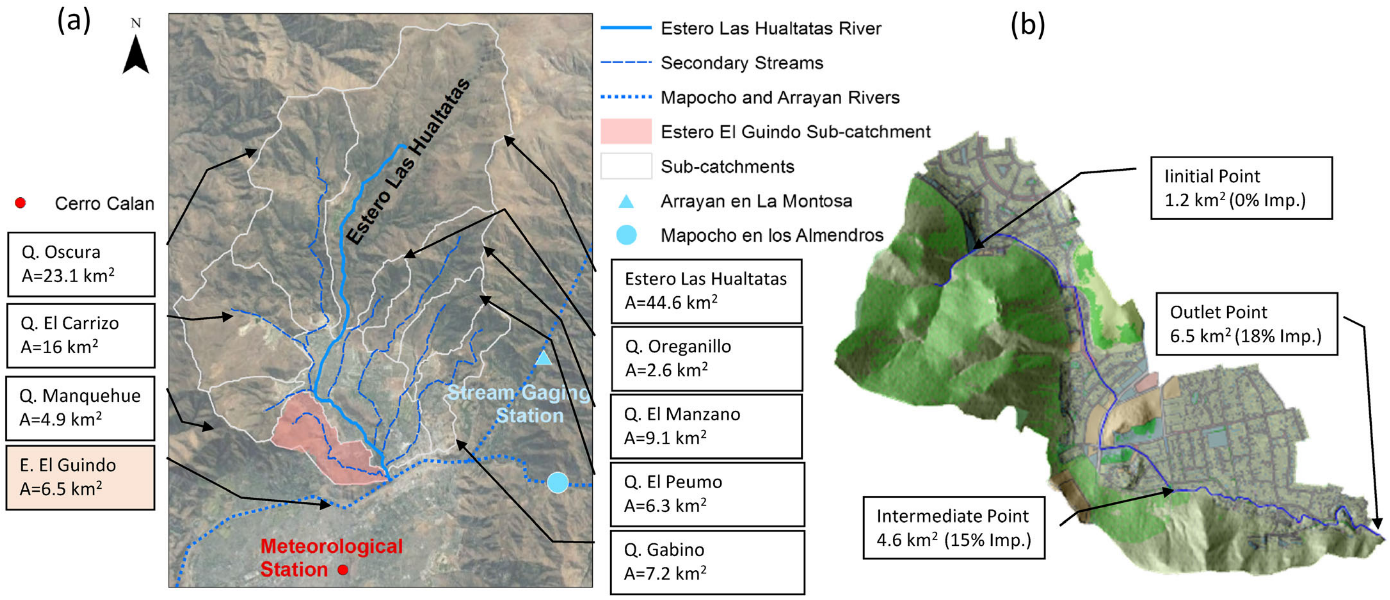

FIGURE 2. (a) Estero Las Hualtatas catchment and its main subcatchments. The figure also shows the stream gauge Arrayan en la Montosa (sky blue triangle) and meteorological station Cerro Calan (red circle). (b) Estero El Guindo subcatchment and flow discharge measurement points (Initial, Intermediate, and Outlet Points).

level. Baseflow is generated by groundwater reaching the stream downstream the Initial Point. In this location, the groundwater table depth fluctuates between 2 and 5 m below the surface, with the stormwater sewers being located deeper.

Different land uses have taken place in the catchment in the last years, as illustrated in Figure 3. In fact, the neighborhood name (i.e., La Dehesa) refers to a type of landscape, typical of Mediterranean climates with trees, pasture, and agricultural lands with no irrigation systems (Figure 3), which existed until the 1950s. At the time, most of the natural vegetation was removed and replaced by pastureland and crops irrigated by ditches and channels. In the subsequent decades, the area was abandoned and the landscape was dominated by thorny shrubs and small herbs (De la Barrera et al. 2016). Since 1980, a rapid urbanization process started in the catchment (Figure 4), and currently most of the flat areas in the lowest part are covered with a low-density urban typology, with commercial activities and services, as well as many irrigated vegetated areas, such as local squares, parks, and sport centers (De la Barrera et al. 2016).

Description of La Dehesa Aquifer

The La Dehesa aquifer is located in the depression of a valley surrounded by mountains with steep slopes. Its boundaries are rocky outcrops in the north, east, and west. In the south, the boundary is the intersection of the Estero Las Hualtatas with the Mapocho River (Figure 1d). The main slope (8%)

FIGURE 3. Schematization of the land use evolution in the study area. From left to right: natural vegetation, agricultural and/or pasture use, thorny shrubs and small herbs, sub-urban use with low residential density and a heterogeneous vegetation, and urban use development with a higher residential density and more trees.

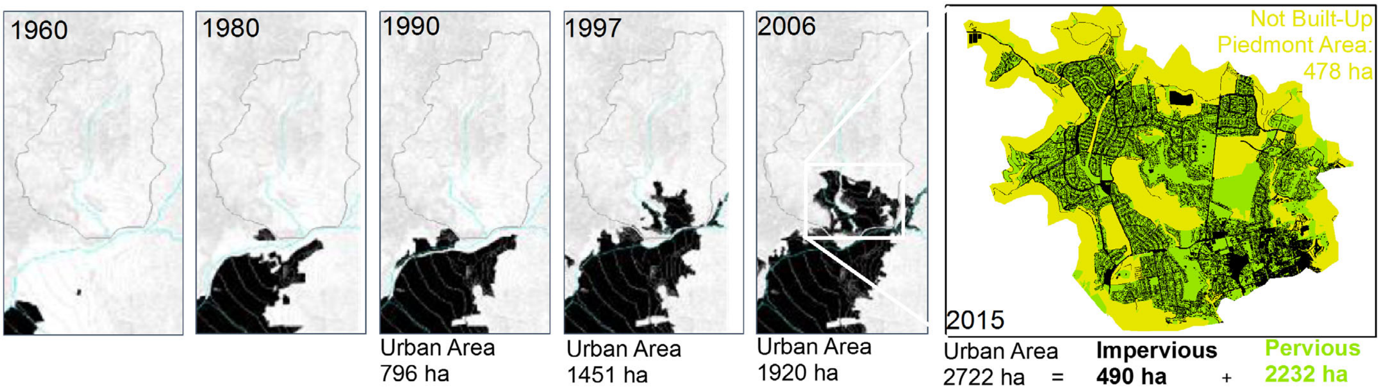

FIGURE 4. Urban growth (black color) of Santiago in the direction of the Estero Las Hualtatas subcatchment for the period 1960–2006 and detailed land use digitalization update as of 2015. The developed area is composed of impervious (18%) and pervious (82%) surfaces.

generates a natural drain and the aquifer almost totally coincides with the urban area (~80% of the aquifer is below this area). Figure 5 shows the geology of the aquifer obtained from previous studies (Alamos and Peralta Ingenieros Consultores 1989; Wall et al. 1999; Muñoz et al. 2003; PRC-Lo Barnechea 2014). The base of the aquifer is formed by volcanic rocks with sedimentary rocks, and the nonconsolidated materials are fluvial, alluvial, fluvioglacial, and gravitational deposits (Wall et al. 1999; Muñoz et al. 2003; PRC-Lo Barnechea 2014; Reyes 2017). The fluvial deposits are formed by quarry stones, gravels, and rubbles in a sand matrix with a low proportion of fine sediments (<40%) (Wall et al. 1999). The alluvial deposits, located in the north and southeast area, are formed by gravels, sand, and fine rubbles in a medium and fine sand matrix composed of silt and clay (>40%) (Wall et al. 1999).

Figure 5 also shows three particular sectors of interest: Sector A (headwater of the aquifer), Sector B (sector with the highest density of extraction wells), and Sector C (sector located downstream the areas of stream–aquifer and stormwater pipe–aquifer interactions). Sector B, called Los Trapenses, also has a high natural groundwater storage capacity, which could be used to a larger extent by building a groundwater dam (Alamos and Peralta Ingenieros Consultores 1989). Cross section B–B (Figure 5) in the Sector B shows that the aquifer has a maximum depth of ~100 m, while the distance between the surface and the bedrock deposit in the boundary between Sector B and Sector C is ~30 m.

MATERIALS AND METHODS

Data

Much of the available information for the area came from the drinking water company, Grupo Aguas S.A., which includes historical well extractions (1990–2016) and groundwater level records (2004–2016). Reyes (2017) validated this information and extended the groundwater level record for the period 1998–2016, whereas the Dirección General de Aguas (DGA; Water National Agency in Spanish) provided information on groundwater levels for the period 1990–1998. Baseflow data were collected in three points of Estero El Guindo subcatchment, which only covered a small fraction of the study area, between June and November, 2015 (Figure 2b). Unfortunately, no streamflow record is available for the Estero Las Hualtatas catchment. Daily temperature and precipitation series for the period 1990–2016 were recorded at the Cerro Calan rain gauge, located near Estero Las Hualtatas catchment (Figure 2a). The orographic effect on precipitation was considered through a logarithm variation of the rainfall R with altitude z, according to the following equation (CCG-UC 2016):

$$R(z) = 109\mathrm{In}(z) - 460, \qquad (1)$$

where R is in mm and z is in m a.s.l. Note that the increasing rainfall rate with elevation takes into account that the occurrence of snow is limited to

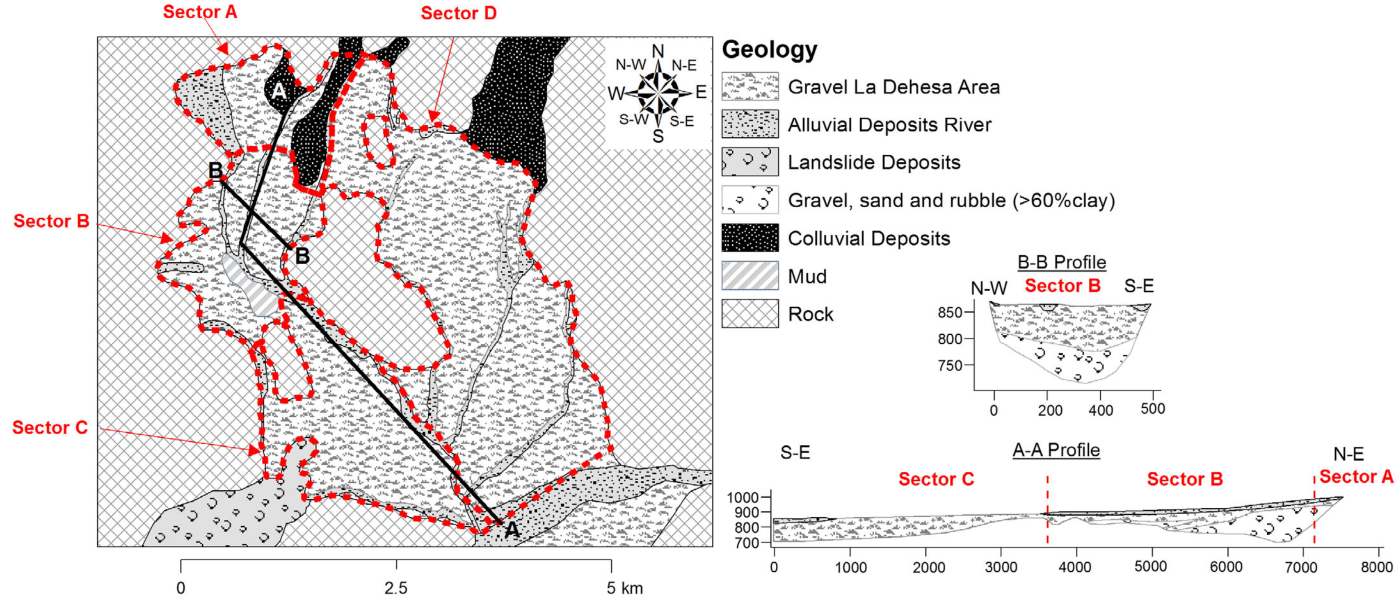

FIGURE 5. Geology of La Dehesa aquifer. Profiles A–A and B–B are the vertical and perpendicular views of the Estero Las Hualtatas River, respectively.

small regions at higher elevations in the basin. Furthermore, a temperature gradient of −6°C/km was used for the entire 800–2,800 m a.s.l. range (CCG-UC 2016). Series of urban growth (Figure 4) were extracted from digitalized maps produced by De la Barrera et al. (2016), while urban recharge rates were extracted from the estimations by Muñoz et al. (2003) for the study area. Finally, the effect of urban growth on irrigation rates was considered, as discussed later in the paper.

The Coupled WEAP–MODFLOW Model

In order to not only describe, but understand and quantify the linkage between the hydrology of the study area, the activities associated with the urbanization, and the observed aquifer levels and streamflows, we built a coupled surface–subsurface model. A previous study in the area (Alamos and Peralta 1990) using a simple water balance approach could not successfully accomplish this task. Moreover, although a hydrologic model was available for the study area (CCG-UC 2016), its representations of the surface and subsurface interactions as well as the groundwater flow were based on conceptual elements or reservoirs. Such representation is also simplistic to simulate the dynamics of these interactions, and the spatial distribution of groundwater levels and spring flows. In particular, it is not possible to quantify the effect of the urban recharge produced by irrigation and water pipe leaks on these dynamics. Due to the characteristics of the study area and its complex relief, the main hydrological processes to be considered in the coupled model include: snow accumulation and melting in the highest elevations, river–aquifer and artificial channels–aquifer interactions in shallow groundwater areas, the draining effect of pipes and stormwater sewers, groundwater extraction wells, and urbanization growth. Furthermore, the different recharge mechanisms including lateral contributions must also be identified in the model.

To simulate all the processes mentioned above, we coupled WEAP (Water Evaluation And Planning) (Yates et al. 2005a, b) and MODFLOW (United States Geological Survey Modular Ground-Water Model) (Harbaugh et al. 2000). WEAP was chosen to simulate surface hydrological processes due to its suitability to represent natural, high mountain, and urban landscapes, as well as demand sites, and river segments. WEAP uses climate information as input to generate, at a coarse time step in a semidistributed fashion, streamflow and the infiltration that eventually becomes the recharge. Elevation bands are established in the model, which serve as the hydrological unit where climate, soil, topography, surface water hydrology, and land use characteristics are specified. Moreover, WEAP can be coupled with the MODFLOW groundwater model (version 2000), one of the most commonly used numerical models for groundwater representation, which solves the equations governing flow in porous media using a discrete and finite number of distributed points. Hence, MODFLOW produces groundwater levels for each cell of the domain in each simulated period.

Coupling the models with different spatial representations implies connecting elements from different spatial domains and different topologies (Figure 6). The terrain in WEAP is represented using a semidistributed mesh, while MODFLOW uses a completely distributed model mesh. Between these two models, a bidirectional exchange of fluxes at each time step is established (Figure 6b). For each time step, WEAP results (i.e., recharge and river stage) and the series of groundwater pumping rates, originally entered to the WEAP model, are loaded into the MODFLOW input files. In turn, MODFLOW runs for one time step producing hydraulic heads in each cell and flows between the surface and groundwater. These results are entered into WEAP to run the next time step (Sieber and Purkey 2015). Among the various Geographic Information System (GIS) tools that can generate the link between WEAP and MODFLOW (Sieber and Purkey 2015), we used LinkKitchen (BGR 2012).

Implementing the coupled model implied the modification of models already built independently for the study area. The WEAP component was based on the monthly basis model built by CCG-UC (2016) for the high mountain area of the Maipo catchment. This model is a refined version of the original model development by Meza et al. (2014), which was subsequently used by Bonelli et al. (2014) in the design of a general framework for evaluating urban adaptation strategies, and by Vicuña et al. (2018) in the evaluation of option contracts to cope with water shortage caused by extreme events. Through its evolution, the WEAP model has been successfully calibrated and validated using streamflow data collected in other tributaries of the Mapocho River, to which Estero las Hualtatas drains. None of the streamflow gauges is located in the study catchment, with the Mapocho in Los Almendros gauge being the closest one, at 6.9 km upstream the catchment outlet along the Mapocho River (Figure 2). Overall, simulated streamflows are the most trustworthy output from this model. On the other hand, the MODFLOW component of our coupled model is based on that developed for the headwater area of the Mapocho River basin, which was provided by the DGA. This model was initially implemented and calibrated for the period 1990–1998 by Muñoz et al. (2003) and later used by DGA-Arrau (2008). Because the original WEAP model (CCG-UC

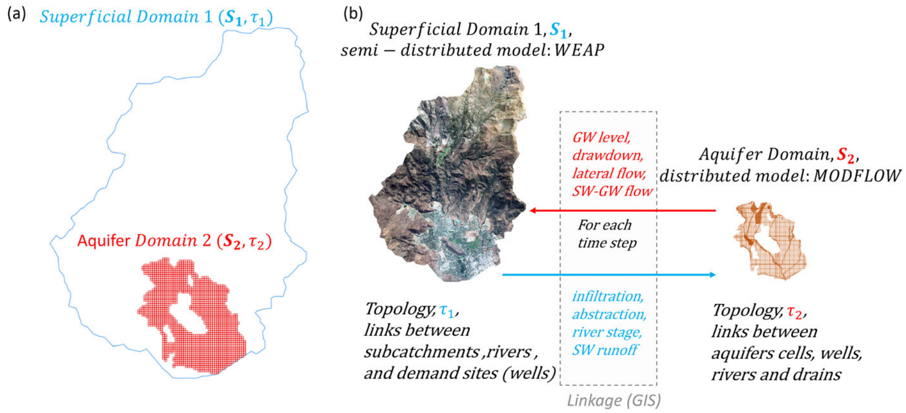

FIGURE 6. Coupling scheme of the hydrological–groundwater models with different spatial domains and topologies among their elements (S,τ) (a), and the bidirectional exchange of fluxes occurring at each time step, where a linkage file (GIS) is used to connect the models. (b) Fluxes from surface water (SW) to groundwater (GW) model are in blue; fluxes from GW to SW are in red.

2016) will be linked to MODFLOW in our coupled model, the calibration and the simulated streamflows will be different. In fact, these flows will now be simulated considering explicitly the MODFLOW routines to model return flows from the aquifer.

The WEAP hydrological model initially considered seven elevation bands. For our study, these bands were extracted for all the subcatchments in the Estero Las Hualtatas, and were subsequently subdivided into 41 hydrological response units (HRUs), i.e., simple polygons with hydrological homogeneous properties for hydrological modeling (Flügel 1995). The HRUs were obtained from the intersection of the elevation bands, the division of the subcatchments, and the geology of the aquifer (Figure 7a). This subdivision rendered the coupling with the groundwater model more flexible. Moreover, the groundwater model was refined at the borders considering the geological information gathered by Alamos and Peralta Ingenieros Consultores (1989), Wall et al. (1999), Muñoz et al. (2003), and PRC-Lo Barnechea (2014). The modeling regular grid of the La Dehesa aquifer (Figure 7b) had 6,410 active cells with a resolution of 50 × 50 m, each one having specific properties (demand, land use, and hydraulic conductivity). The downstream boundary condition in the south corresponds to the intersection with the Mapocho River and was represented by a constant hydraulic head, but variable in time.

Finally, the coupled model of the Estero Las Hualtatas catchment and La Dehesa was represented using 43 basins, 38 wells, 12 river ranges, 84 infiltration links, 38 transmission links, and 4 return flow links. Figure 8 shows the topology of the different elements of Estero Las Hualtatas River and La Dehesa aquifer. The groundwater model considers

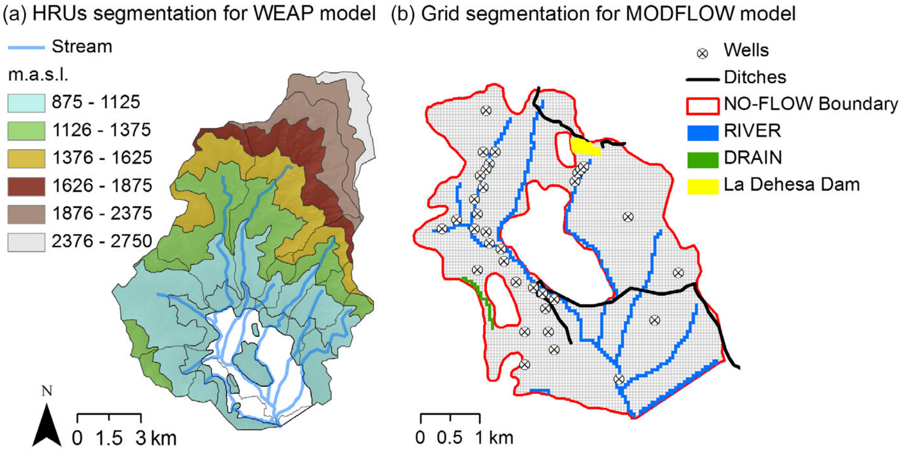

FIGURE 7. Hydrological response units (HRUs) mesh and boundary conditions of the hydrogeological model. (a) Elevation bands and HRUs used in Water Evaluation And Planning (WEAP), (b) modeling grid for the MODFLOW model of La Dehesa aquifer.

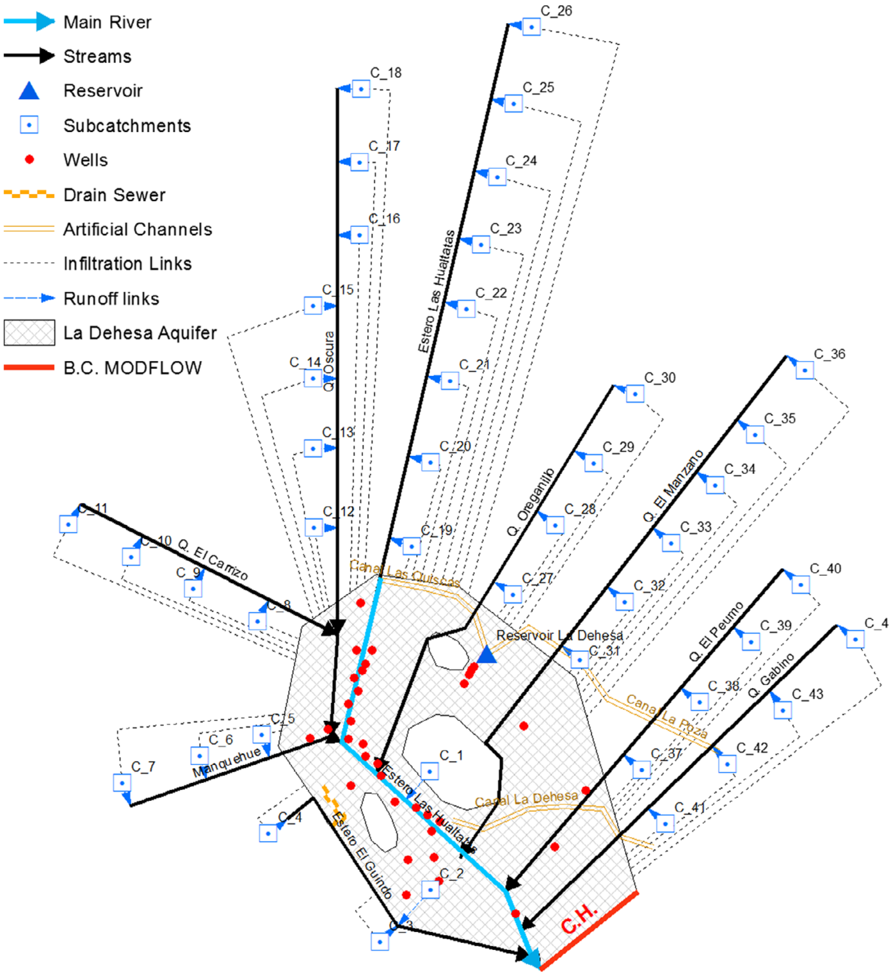

FIGURE 8. Topology of the coupled hydrological–groundwater model of the Estero Las Hualtatas catchment and La Dehesa aquifer. The boundary condition, C.H., means Constant Head.

the river elements (which allow the river–aquifer interaction), the drain elements (which allow the exfiltration of groundwater to surface elements), wells, and the constant head boundary condition. The time step used in the coupled model was one week.

While WEAP produces the recharge due to precipitation in the catchment (i.e., both over the aquifer and the lateral one), the recharge due to percolation from water pipe leaks and irrigation of green areas (hereafter referred to as urban recharge), must be entered directly as an input to WEAP. In turn, this model transfers directly this information to the MODFLOW model. Figure 9a shows the monthly estimated urban recharge obtained from the study by Muñoz et al. (2003), who used a numerical model to estimate infiltration from irrigation data as proposed by McNeilege (1989), and water losses from distribution networks data reported by the water supply companies in the area (i.e., ~0.08–0.15 L/s/km of pipe). This urban recharge is presented on a monthly basis in Table 1 and considers two urban land uses: (1) urban consolidated and (2) single-family residential area. In our work, these recharge rates for each land use were assumed to be valid over the whole simulation period, whereas the total urban recharge was obtained by multiplying the rate of each land use by the corresponding area. Thus, the resulting time series of total urban recharge takes into account the evolution of the land uses and the overall urban development through time (Figure 9a). Finally, groundwater pumping rates are other relevant information provided to WEAP that is directly transferred to MODFLOW. Figure 9b shows the total observed series of groundwater pumping rates from the wells reported by the drinking water company and other recreational and educational institutions in the area.

Calibration and Validation

The coupled model was calibrated and validated during the 1990–2005 and 2006–2017 periods, respectively.

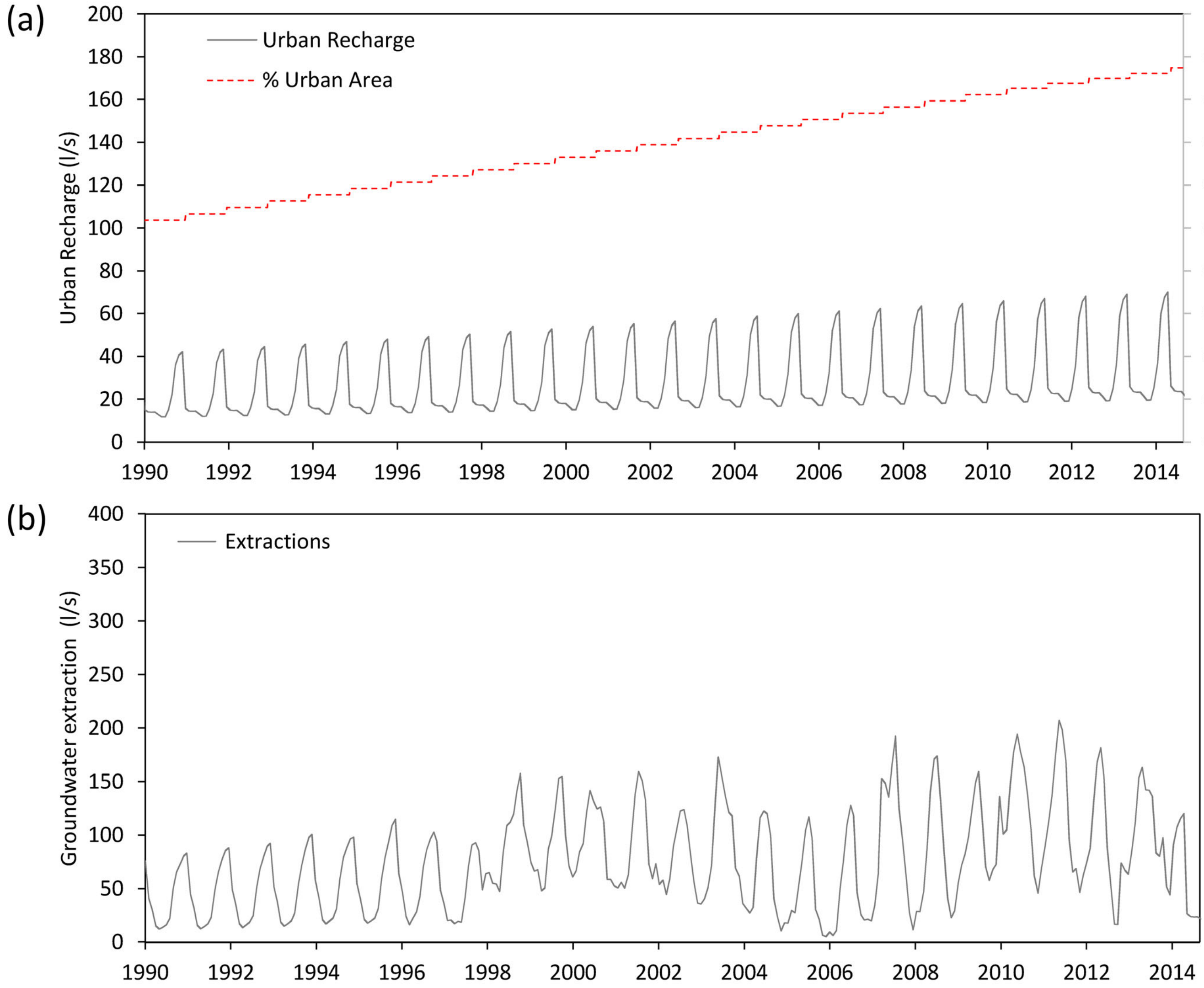

FIGURE 9. Urban recharge due to irrigation and pipe leaks (a), and groundwater pumping rate (b).

As a starting point, we used the previously calibrated WEAP parameter values from CCG-UC (2016) and the MODFLOW parameter values from Muñoz et al. (2003) and the official model provided by the DGA. The calibration focused on representing well all the information available, including: (1) monthly flow series produced in the catchment outlet by the existing WEAP model (CCG-UC 2016), from now on also referred to as the reference flow discharges, (2) observed daily flows representative of the baseflow measured between June and November, 2015 in the Estero el Guindo subcatchment, and (3) groundwater levels recorded in observation wells. The existing WEAP model simulations are used as a reference for the calibration due to the extensive use of the model in previous work reported elsewhere (Bonelli et al. 2014; Meza et al. 2014; Vicuña et al. 2018).

Definition of Scenarios

To quantify the effects of urban growth and urban recharge due to pipe leaks and irrigation rates, two future scenarios were evaluated in a 20-year horizon. Both scenarios assumed the following: (1) the urban land use varied from 84% to 95%, (2) the current drinking water demand increases in 60%, and (3) the climate remains the same, which in turn implied repeating the precipitation and temperature series from the past 30 years (1987–2017). This last assumption was made to isolate the impacts of demographic and land use changes from those of climate change. The scenarios under consideration are:

1. Scenario I: scenario with an increase in irrigation demands but under current irrigation rates.
2. Scenario II: an extreme water conservation scenario in which leaks are reduced and green areas

TABLE 1. Urban recharge in mm/month for urban land uses estimated by Muñoz et al. (2003).

Urban land use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Urban consolidated	9.4	9.4	8.5	7.7	5.9	5.1	5.1	5.1	5.9	6.8	7.7	8.5
Single-family residential area	15.4	16.0	8.3	6.2	4.7	4.1	4.1	4.1	4.7	5.4	7.4	13.3

TABLE 2. Range of the parameters calibrated for 41 hydrological response units (HRUs) of the Estero Las Hualtatas catchment and for the groundwater model of La Dehesa aquifer.

Sector	Parameter	Unit	Description	Model	Range of calibrated values
Hillslope	K_c	—	Crop coefficient	WEAP	0.50–1.20
	S_w	mm	Root zone water capacity	WEAP	300–1000
	RRF	—	Runoff resistance factor	WEAP	0.07–2.88
	K_s	mm/week	Root zone conductivity	WEAP	94–118
	PFD	—	Preferred flow direction	WEAP	0.03–0.22
La Dehesa aquifer	K_c	—	Crop coefficient	WEAP	0.50–1.20
	S_w	mm	Root zone water capacity	WEAP	300–1000
	RRF	—	Runoff resistance factor	WEAP	0.07–2.88
	K_s	mm/week	Root zone conductivity	WEAP	94–118
	PFD	—	Preferred flow direction	WEAP	0.03–0.11
	$K_{x,y}$	m/day	Hydraulic conductivity	MODFLOW	2.6–100
	S	1/m	Storage	MODFLOW	0.01–0.15
	n	—	Porosity	MODFLOW	0.01–0.25
	K_{BC}	m/day	River conductivity	MODFLOW	0.93–1.63
	K_{Drain}	m/day	Drain conductivity	MODFLOW	2.00

are under good management practices, including (1) a highly efficient irrigation technique and (2) the use of native vegetation. This scenario implies a 90% reduction of the current recharge rates, which implies reducing from an annual average of ~7 mm/month in urban land uses (Table 2) to 0.7 mm/month.

RESULTS AND DISCUSSIONS

Model Calibration and Validation

Table 2 summarizes the parameters selected for the manual calibration of the coupled model and presents the final range of values adopted after the calibration. The involved WEAP parameters were mainly the hydraulic conductivity of the root zone (K_s), the preferred flow direction (PFD), and the runoff resistance flow (RRF). In MODFLOW, the most sensitive parameters included: the conductivity of the bottom of the river (K_{BC}) and the hydraulic conductivity of the aquifer (K_{xy}).

Figure 10 shows the final calibration of the coupled model to the flow series from the WEAP model by CCG-UC (2016), as well as the flow simulated for the validation period. We used the Nash–Sutcliffe coefficient (NS), determination coefficient (R^2), and mean absolute error (MAE) (Bennett et al. 2013) to assess the goodness-of-fit in both periods. The coupled model replicates well the monthly discharge series for high and low precipitation periods (Figure 10a,b), both for the calibration ($R^2 = 0.967$, NS = 0.956, MAE = 0.172) and validation periods ($R^2 = 0.973$, NS = 0.972, MAE = 0.093). The good agreement between the flows simulated with both models is also observed when comparing the flow duration curves, i.e., the curve showing the percentage of time for which a certain flow is exceeded (Figure 10c). The coupled model produces very similar high flow values, although higher low flow values are provided. Such difference explains the higher average baseflow between December and March simulated by the coupled model (Figure 10d). Moreover, the model simulates an average annual flow of 0.81 m^3/s for the period 1990–2015, only 20 L/s above the average of the reference flow discharges (i.e., 0.79 m^3/s).

Separating baseflow from surface runoff is not obvious, but Pyerce (2004) suggests using the 95%, 90%, and 75% exceedance probabilities to estimate base and low flows. Table 3 compares monthly average values associated with these quantiles simulated with the coupled and the reference model at the outlet of Estero Las Hualtatas River.

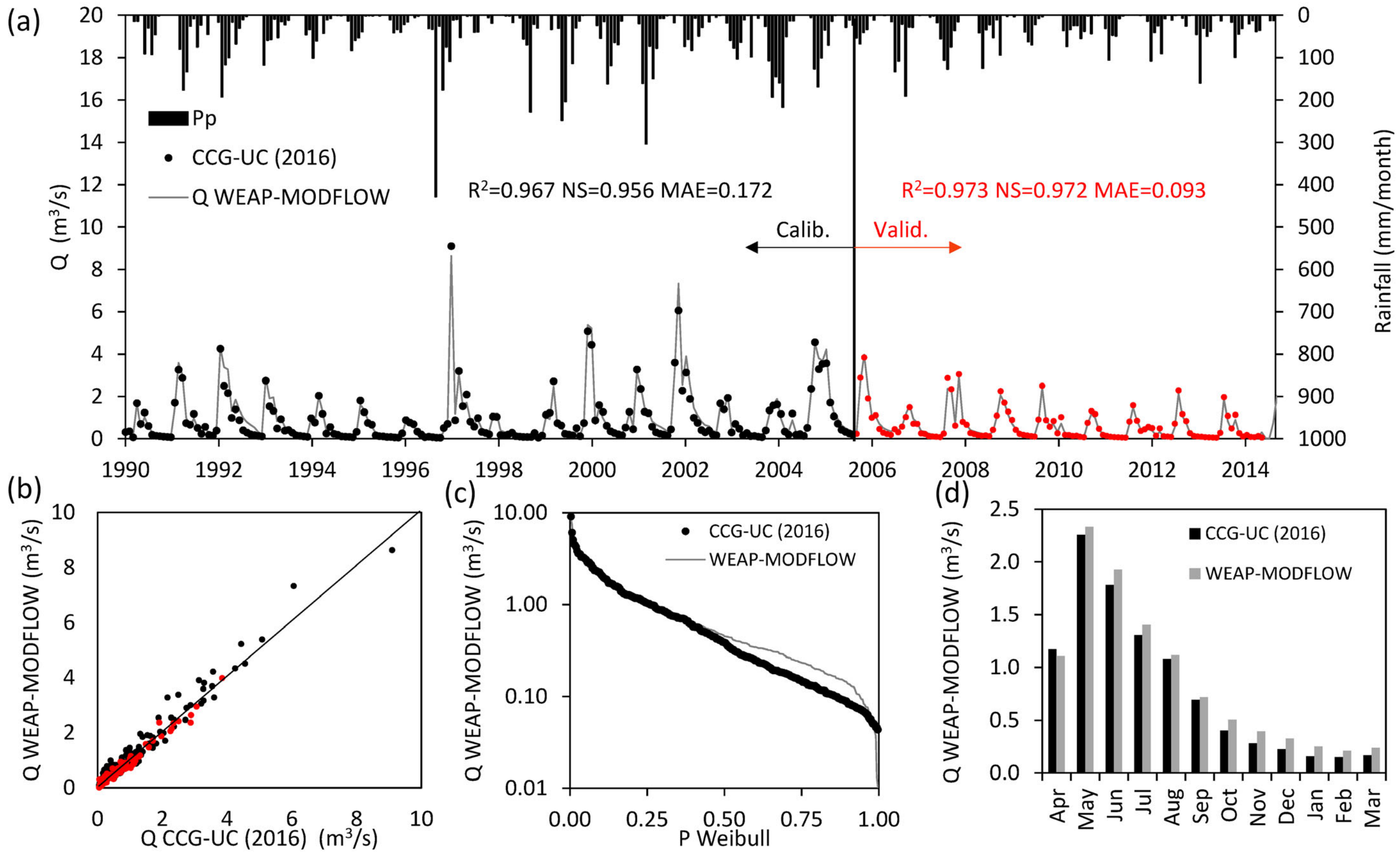

FIGURE 10. Comparison of flows simulated by the coupled WEAP–MODFLOW vs. the reference model (CCG-UC 2016). (a) Monthly series for the calibration and validation periods, (b) correlations between monthly values for both calibration and validation periods, (c) flow duration curves, and (d) monthly average streamflows.

The coupled model is further validated by comparing the simulated specific yield (i.e., flow rate per unit of area) against the observed value at the stream gauge Estero Arrayan en la Montosa, the neighbor catchment located upstream, which also contributes to the Mapocho River (Figure 2). For the same period (1990–2015), a specific yield of 6.2 L/s/km^2 was reported by the Chilean Water Agency in this catchment, while a value of 5.8 L/s/km^2 was simulated for the Estero Las Hualtatas catchment. The minor discrepancy is possibly due to the additional contribution from snowmelt observed in the Arrayan en la Montosa during the dry season, which does not take place in the Estero Las Hualtatas catchment.

A final validation focused on the baseflows is shown in Figure 11, which compares the simulated and observed daily flows between July and October, 2015, in the Initial, Intermediate, and Outlet Points of the Estero El Guindo subcatchment within the study catchment (Figure 2). For the comparison, the calibrated coupled model was implemented on a daily basis for the 2013–2017 period. Because the hydrographs could not be well recorded in the initial point due to the low water depths and the irregularity of the section, we could only register the time periods with null and no-null flows (Figure 11a). As this point is representative of the natural peri-urban zone, streamflows do not occur, unless it is raining. This behavior is well captured by the coupled model. On the other hand, null daily flows were neither recorded nor simulated in the Intermediate and Outlet Points (Figures 11b,c). Although the simulated and observed values do not match very well, they follow alike dynamics within similar ranges.

Furthermore, we compared the simulated and observed flows with exceedance probabilities of 75%, 90%, and 95% for the Intermediate and Outlet Points. These values are of high interest because they reflect the river–aquifer interactions, as the river bed and the stormwater pipes are located below the groundwater level in this subcatchment. Table 4 shows that these flow discharges are very similar. Note that the intermediate point is below the water table located upstream, so its flow is strongly influenced by river–aquifer interactions. On the other hand, surface water along the stream portion between the

TABLE 3. Reference and simulated monthly low flows associated with high exceedance probabilities in Estero Las Hualtatas River.

$P_{\mathrm{Exc.}}$	Reference Q_{Sim} (m^3/s)	Q_{Sim} (m^3/s)
$Q_{50\%}$	0.386	0.452
$Q_{75\%}$	0.143	0.230
$Q_{90\%}$	0.082	0.136
$Q_{95\%}$	0.068	0.083

Intermediate and Outlet Points tends to flow back to the subsurface. This is also simulated by the coupled model to a good extent.

The groundwater levels simulated by the coupled model were also compared against those observed for the period 1990–2005 (calibration) and 2006–2015 (validation) (Figure 12). This comparison is very valuable because it strengthens the calibration/validation using the simulated reference flow discharges. In general, the model is able to represent decreasing and increasing trends observed in the monitoring wells (e.g., the drought periods 1995–1997 and 2010–2015), and the overall groundwater levels across the different sectors are well simulated. To illustrate the quality of the model, Figure 12 compares the observed and simulated groundwater levels at five different wells within sectors A, B, and C. Satisfactory R^2 values of 0.66 and 0.9 were obtained for the Valle Cordillera and the 2,101 wells, respectively, for the totality of the calibration and validation periods. Note that simulated groundwater levels are more variable in time than the observed levels, as the simulated monthly values average four weekly values, while the observed values correspond to observations in a random day during each month. The inter-seasonal variation of groundwater levels in Sector A (well 3,217) is explained by the hydrologic response of the Estero Las Hualtatas — a high mountain catchment — whose contribution highly influences the recharge. On the other hand, Sector B (La Dehesa and Valle Cordillera wells) presents a buffered response due to the high storage capacity in the aquifer; which is estimated to be 25 × 10^6 m^3 (Alamos and Peralta Ingenieros Consultores 1989). Finally, Sector C, downstream from the high storage capacity sector (wells 2,101 and 2,109), receives overflows from Sector B, the neighbor recharge of the Estero El Guindo subcatchment, and a large part of the infiltration recharge associated with pipe leaks and urban irrigation. Overall, the coupled model not only produces streamflows similar to those of the reference model, but it is also able to represent the observed dynamics of the groundwater, which in turn explains the good simulation of the baseflow presented previously.

Furthermore, one of the most important results obtained with the coupled model was the estimation of the lateral recharge. Figure 13 shows the total simulated lateral recharge series from all the catchments contributing to Estero Las Hualtatas, which corresponds to the main input at the boundary of the La Dehesa aquifer. This recharge is directly related to the occurrence of rainfall events, and thus it decreases rapidly after the winter season. As expected, because of the size of the catchment study, the lateral recharge is the most important source of recharge to the aquifer (~9 times larger than the urban recharge).

Sensitivity Analysis and Implications of the Coupled Model

We performed a one-factor-at-a-time sensitivity analysis to assess the relevance of the input variables and parameters over the output of the coupled model (i.e., the streamflow at the outlet of the Hualtatas catchment and the average groundwater level of the aquifer). The analysis used MAE as the objective function and considered variations in the ±50% range for the most critical input variables involved in the simulation of the aquifer recharge and the groundwater flow: (1) the lateral recharge (i.e., the flow

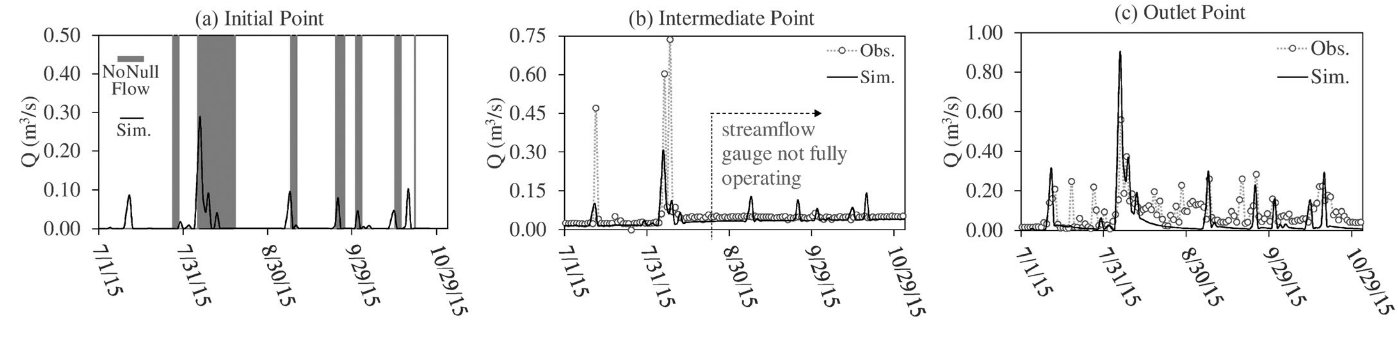

FIGURE 11. Simulated and observed daily flows in the three monitoring sites: Initial Point (a), Intermediate Point (b), and Outlet Point (c). Only time periods with null and no-null flows could be identified for the Initial Point.

TABLE 4. Simulated and observed daily low flows associated with high exceedance probability (baseflow) in the Estero El Guindo.

$P_{\text{Exc.}}$	$Q_{\text{Obs.Interm.}}$ (m^3/s)	$Q_{\text{Sim.Interm.}}$ (m^3/s)	$Q_{\text{Obs.Outlet}}$ (m^3/s)	$Q_{\text{Sim.Outlet}}$ (m^3/s)
$Q_{75\%}$	0.026	0.017	0.020	0.018
$Q_{90\%}$	0.025	0.016	0.018	0.015
$Q_{95\%}$	0.024	0.015	0.017	0.013

Note: Observed flows were recorded during June–November, 2015.

simulated from WEAP to MODFLOW from the lateral basins), (2) the hydraulic conductivity of the surface soil layer (K_s), and (3) the hydraulic conductivity of the aquifer (K_{xy}). Although not a parameter, the lateral recharge was studied to understand its role in the overall response of the surface–aquifer system. To vary this recharge, precipitation in lateral catchments was decreased/increased accordingly. On the other hand, K_s is the WEAP parameter controlling the infiltration flow into the first reservoir representing the first soil layers, and K_{xy} is the MODFLOW parameter representing the flow capacity in the deep strata containing the aquifer. Because the aquifer covers a small region of the basin, the lateral recharge to the aquifer is the most influential variable on the surface–aquifer dynamics of the model. This recharge, and the precipitation that originates it, in turn become the most relevant input for the MODFLOW model. This is illustrated in Figure 14, first column, which shows significant changes both in the surface flow and groundwater levels. Variation in K_s does not affect substantially either of these output variables (Figure 14, second column), indicating that the recharge due to precipitation over the area covered by the aquifer is not relevant. Finally, variations in K_{xy} significantly affect only groundwater levels (Figure 14, third column). Other important parameters detected during the calibration processes were the PFD and RRF in WEAP, and the riverbed conductivity (K_{BC}) in MODFLOW.

Overall, the sensitivity analysis demonstrates the relevance of a good characterization of the riverbed material and the different strata containing the aquifer. Moreover, the results show the importance of a good spatially distributed measurement of the rainfall, a fundamental driver of the lateral recharge in the area. This is particularly critical in areas with complex relief, like the one under study, where spatial rainfall variations may need to be represented with models more sophisticated than the simple regression expressions typically used, such as that in Equation (1).

Effects of Future Urban Growth and Urban Irrigation Rate

Due to its good representation of both surface and groundwater variables, we ran the coupled model to

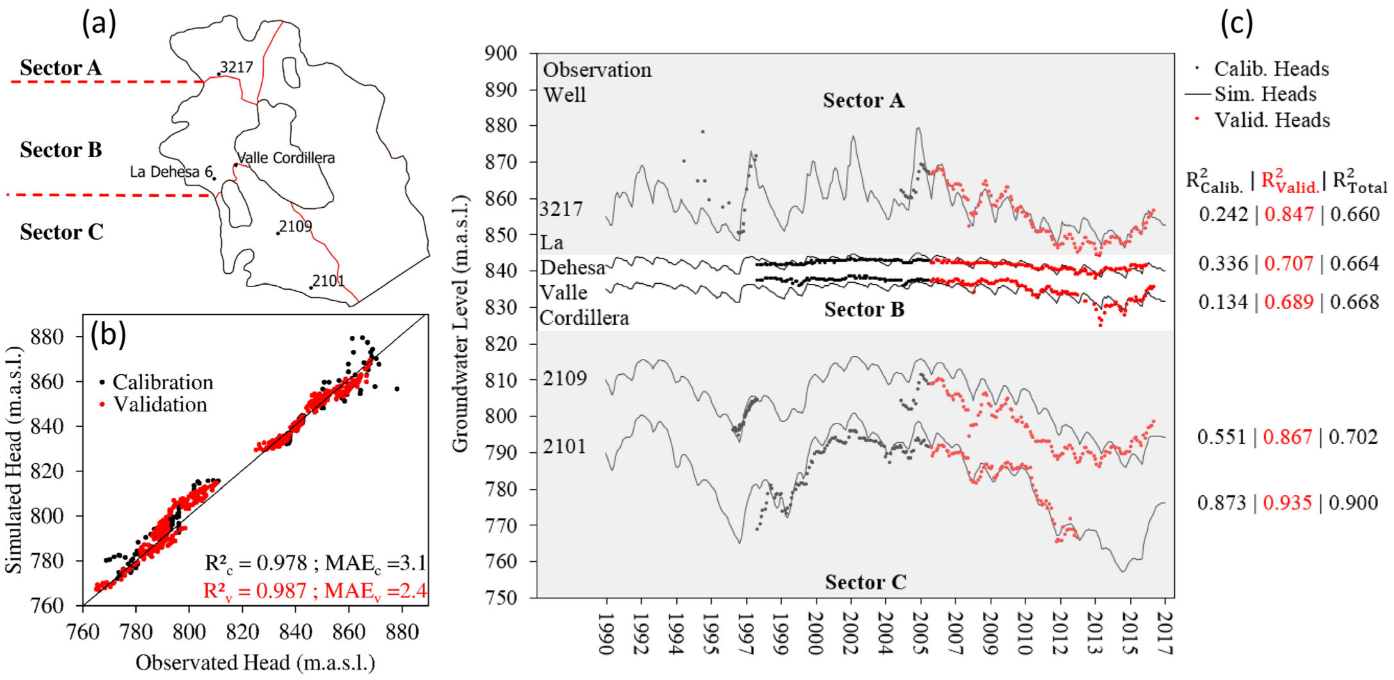

FIGURE 12. Comparison of observed and simulated groundwater levels. (a) Location of observation wells in La Dehesa aquifer, (b) observed and simulated hydraulic heads for calibration (black) and validation (red) periods, and (c) time series of observed (black and red dots) and simulated (line) groundwater levels.

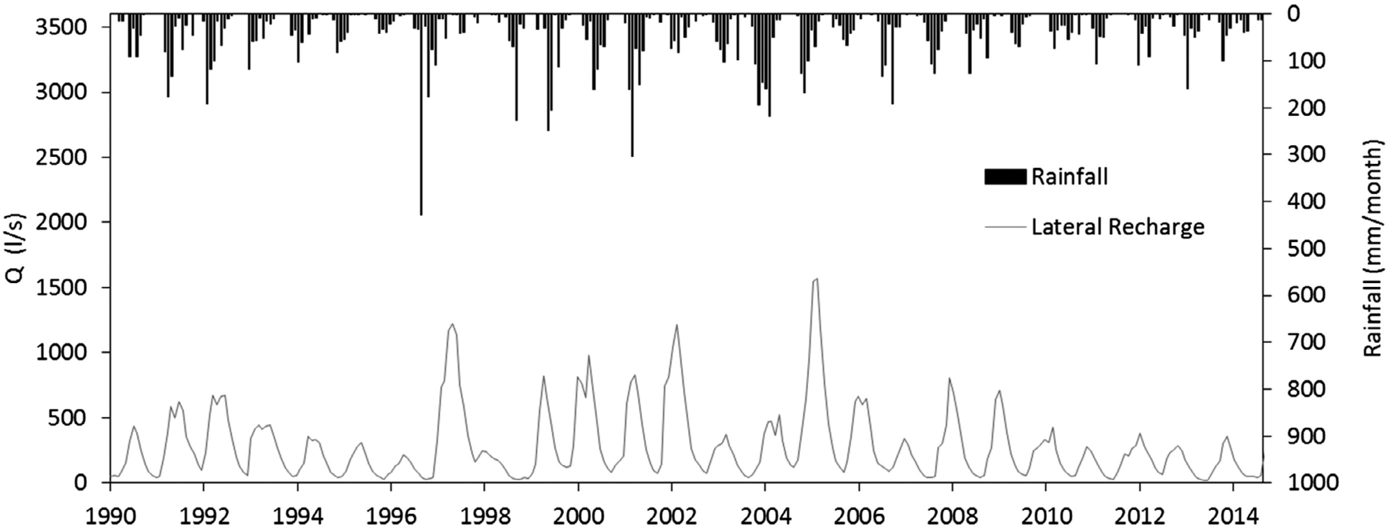

FIGURE 13. Simulated lateral recharge of La Dehesa aquifer.

compare the future scenarios previously defined. Table 5 compares the mean, minimum, and maximum spatial averaged simulated aquifer levels at Sectors A, B, and C for both scenarios.

It is observed that the mean level decreases in 0.9, 0.4, and 0.8 m for sectors A, B, and C, respectively, for Scenario II (i.e., reduced irrigation rates and pipe leaks) as compared to Scenario I (i.e., current status). On the other hand, the differences between the minimum average values between both scenarios are 1.5, 1.3, and 1.4 m a.s.l., while the differences between the maximum average values are 0.4, 0.1, and 0.3 m a.s.l., respectively. Because these values correspond to average differences, more significant changes can

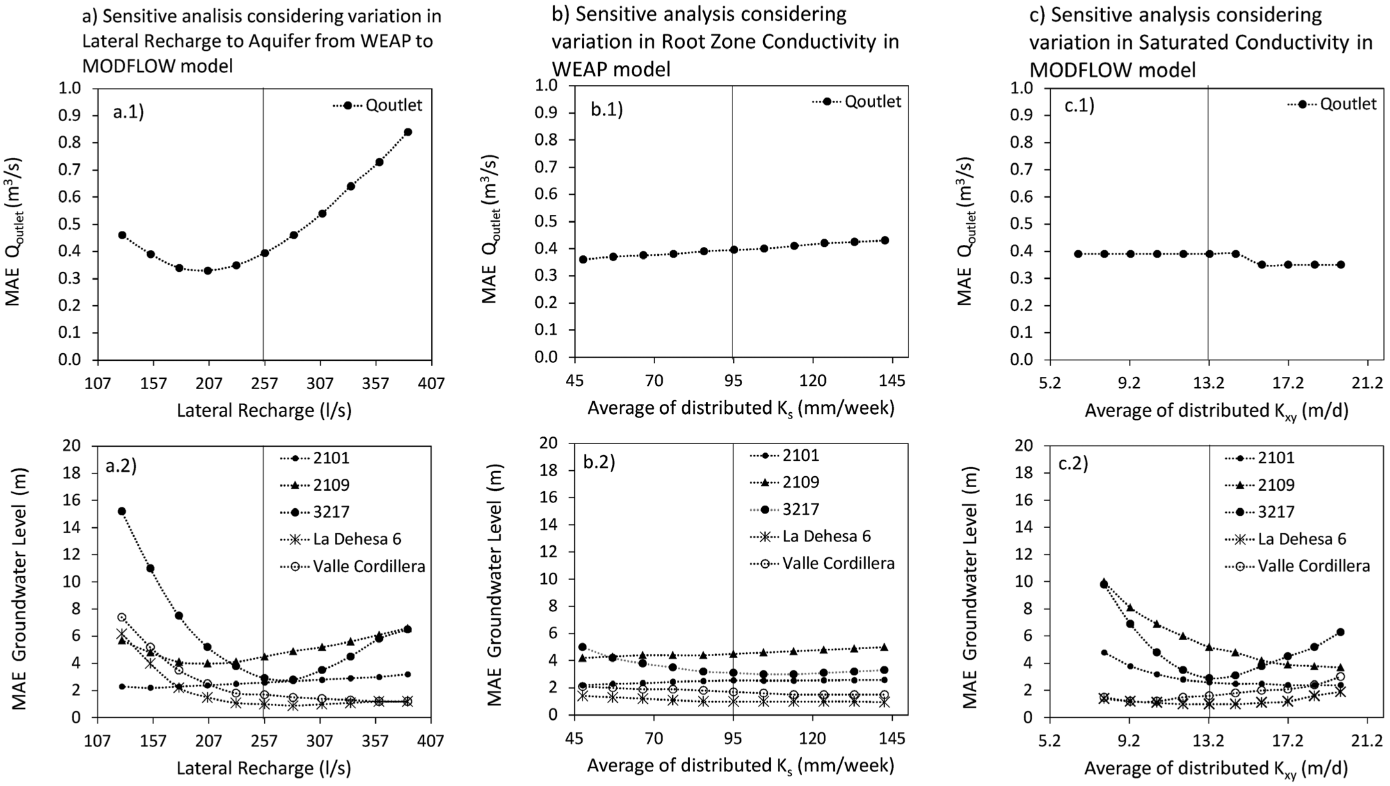

FIGURE 14. Evaluation of different scenarios and their effect on the groundwater levels and baseflow (a.1; b.1; c.1) and groundwater levels (a.2; b.2; c.2) for Lateral Recharge, Root Zone Conductivity, and Saturated Conductivity.

TABLE 5. Groundwater levels for Scenarios I and II at different aquifer sectors.

Groundwater level (m a.s.l.)	Scenario I			Scenario II		
	A	B	C	A	B	C
Mean	870.8	846.3	805.6	869.9	845.9	804.8
Minimum	853.2	838.0	786.8	851.8	836.7	785.4
Maximum	912.5	854.0	816.4	912.1	853.9	816.1

TABLE 6. Simulated median and base monthly flows associated with Scenario I and Scenario II.

$P_{\text{Exc.}}$	$Q_{\text{Scenario I}}$ (m^3/s)	$Q_{\text{Scenario II}}$ (m^3/s)
$Q_{50\%}$	0.408	0.389
$Q_{75\%}$	0.198	0.183
$Q_{90\%}$	0.105	0.086
$Q_{95\%}$	0.043	0.022

take place in specific locations within the sectors. These results must be treated carefully due to the uncertainty of the model and its errors, which can be in the order of 2–3 m in some locations for the study period (Figure 12). As the decrease in groundwater levels directly affects the streamflow, a reduction in the average flow ($Q_{50\%}$) from 408 to 389 L/s is estimated in the Estero Las Hualtatas, while the low flows ($Q_{95\%}$) would decrease from 43 to 22 L/s, as shown in Table 6. Overall, a more efficient water use scenario implies decreasing returning flows to the aquifer, limiting its current recharge and reducing the water table level.

Positive Externalities from the Inefficient Use of Urban Water

Typically, leaks of drinking water and incidental (or even accidental) discharges from various practices associated with the handling of sewage effluents and wastewater reuse are main contributions to the aquifer recharge in urban settings (Foster and Chilton 2004). In addition to leaks of drinking water corresponding to ~20% of losses in the area (SISS 2016), in the Estero Las Hualtatas catchment and the La Dehesa aquifer, a significant part of the urban recharge also corresponds to the returning flows from high irrigation rates. Overall, according to our results, both sources of recharge add up to ~10% of the total recharge to the La Dehesa aquifer.

As water resources become scarcer, there is an increasing demand for improving the efficiency of water use in the urban landscape (Hilaire et al. 2008). Interestingly, an increase in the efficiency of urban irrigation and pipe leak control will reduce water demands currently supplied using resources from a neighbor catchment, but will affect negatively the water table levels in the study area. In fact, the Sector B of the La Dehesa aquifer has been proposed as a sector for a possible underground reservoir (Alamos and Peralta Ingenieros Consultores 1989) due to its high storage capacity. In fact, the authors proposed an artificial groundwater dam and a boost of artificial recharge to increase the storage during dry times. However, with the expansion of the city and the introduction of vegetation in the urban area, irrigation rates currently boost recharge during the whole year at a fairly constant rate. This has helped limiting the groundwater level decrease and favor water availability during dry seasons. Hence, the groundwater dam proposed by Alamos and Peralta Ingenieros Consultores (1989) would protect the extraction wells located in the area from abrupt water table decreases, which in turn implies maintaining a more stable aquifer level. This would benefit the drinking water supply company, which will be more able to satisfy water demands in the area. However, a higher and more stable water table associated in this case with inefficient irrigation rates and pipe leaks implies compromising the water resources of the neighbor catchment from where water is extracted to fulfill the demand in the Las Hualtatas catchment. Thus, a more integrated study across the different spatial scales covering the Maipo River basin is needed to comprehensively address the impacts of urbanization on water resources in the area. Despite the local character of our study, we expect that our results and analysis can help other researchers and practitioners coping with similar situations.

CONCLUSIONS AND PERSPECTIVES

With the objective of identifying and assessing the impact of urban growth and residential irrigation on streamflow and groundwater levels in a peri-urban semiarid catchment, this study built a coupled WEAP–MODFLOW model for the peri-urban catchment Estero Las Hualtatas and La Dehesa aquifer, located in the piedmont region of Santiago, Chile. The model was calibrated and validated using both previously simulated streamflow values and locally observed data. Furthermore, a sensitivity analysis was performed, as well as two simulations to assess the impacts of future water conservation scenarios.

The work allows answering the initial research question: (1) there are significant stream–aquifer interactions in the area due to the shallow groundwater and the lateral and in-situ recharge rates; the representation of these interactions requires using a physically based coupled model able to simulate these interactions at each time step, and their corresponding spatial and temporal dynamics. (2) Pipe leaks and irrigation are significant sources of urban recharge, although less important than the lateral discharge. (3) Reducing this urban recharge will affect the aquifer, although the uncertainty of the model and its errors do not allow being very conclusive about the magnitude of this change. Our main specific conclusions are:

1. The flow series simulated at the catchment outlet were successfully compared against flows previously simulated with a WEAP calibrated model (values of R^2 = 0.66–0.76 were obtained). On the other hand, observed average daily flows measured along a stream located in the catchment were used to successfully verify the low flows estimated by the model, which had differed to some extent with the flows simulated by the original WEAP model. Finally, the model was also successfully validated by comparing simulated and observed monthly time series of groundwater levels in several wells (R^2 values between 0.603 and 0.9 were obtained).
2. The recharge due to the inefficiency of house irrigations and water pipe leaks impacts positively the aquifer levels and the baseflow. In fact, the median flow ($Q_{50\%}$) and low flows represented by $Q_{95\%}$ are expected to decrease from 408 to 389 L/s, and from 43 to 22 L/s respectively, when considering a future 90% reduction of the urban recharge rates due to irrigation and pipe leaks. Furthermore, under this scenario, a maximum water table decrease of ~1.5 m is expected. Nevertheless, the errors of the model have an order of magnitude similar to these modeled changes in the water table.

Future work should focus on implementing a continuous streamflow monitoring both at the catchment outlet and in the stream portions and sewers where river–aquifer interactions take place. Furthermore, the effects of high fluctuations in urban irrigation on the river levels could be studied in more detail. For a more realistic assessment of this interaction, and given the semidistributed nature of WEAP, more suitable models for smaller scales should be used to simulate the percolation to groundwater, such as PUMMA (Jankowfsky et al. 2014), URBS (Rodriguez et al. 2008), or IHMORS (Herrera et al. 2017). These models allow the modeling of a root zone layer and the differentiation between interflow and flow to the groundwater. Finally, a continuous monitoring of residential irrigation rates is essential for the use of these models. Alternatively, good estimations from residential water consumptions can also be used, such as those recently published for the city of Santiago by Reyes-Paecke et al. (2019).

The methodology here proposed can be generalized to other peri-urban catchments with strong surface–groundwater interactions, heavily dependent on recharge from natural areas, and with large urban irrigation rates. The setup of the corresponding coupled surface–subsurface model requires quite a large amount of data, particularly groundwater extractions, irrigation practices and rates, as well as rainfall and discharge records. Nevertheless, such investment in data collection is valuable and necessary to design sustainable water resources management practices.

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