

Environmental Science and Pollution Research

Environmental Functions of Biochar

**Guest Editors: Hailong Wang, Yong Sik Ok,
Scott X. Chang, Yongtao Li**

**and
Original Papers**

**Editor-In-Chief
Philippe Garrigues**



Official Organ of the
EuCheMS Division
of Chemistry and the
Environment (EuCheMS DCE)

 Springer



Assessment of vulnerability and control measures to protect the Salburua ecosystem from hypothetical spill sites

Jaime Gárfias¹ · Hilario Llanos² · Richard Martel³ · Javier Salas-García¹ · Luvina Bibiano-Cruz¹

Received: 4 October 2017 / Accepted: 26 June 2018 / Published online: 5 July 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Population pressure, urbanization, and industrial developments, among other factors, have resulted in severe degradation of environmental resources such as wetlands. Thus, a groundwater model (MODFLOW) was integrated with a particle tracking MODPATH model to simulate the hydrodynamic flow head field and to analyze the vulnerability of the Salburua ecosystem and propose control measures to protect the riparian area. The simulations show that pathways of particle tracking originating at potential contaminant sources will tend to migrate downwards towards the sensitive ecosystem, which suggests that the quality of the hydrological ecosystem is likely to deteriorate in the future. Variation in exit points of particles indicates that the time-related capture areas are affected by changes of the hydraulic gradients. Two control measures of potential sources of pollutants in the vicinity of the Salburua ecosystem were analyzed. The study results suggest that the travel time-related capture zone with a funnel-and-gate system is much smaller than without the control alternative, which indicates that the gate configuration has an effect on capture zone size and shape and on the residence time with a better attenuation performance. It is also shown that a leakage-proof barrier is less effective for point-source containment, assuming that hydraulic control performance and cost-efficiency are the criteria for pollution control effectiveness. Instead, a program of monitoring wells would effectively characterize water quality in the aquifer and provide a decision support system. This approach may be used in helping water managers to develop more physically based and quantitative protection strategies.

Keywords Salburua ecosystem · Numerical modeling · Risk pollution · Travel time-related capture zone · Control measures · MODFLOW · MODPATH · Particle tracking

Introduction

Wetlands are one of the most essential environmental ecosystems that normally form on flat regions or gentle slopes, in which water quantity and quality play an essential role in biodiversity conservation. In these environments, riparian zones form a transitional area between terrestrial and water

environments (Gregory et al. 1991), in which superficial and sub-superficial groundwater circulation could converge and upwelling or downwelling physical processes could emerge (Cey et al. 1999; Nwankwor and Anyaogu 2000). In this regard, riparian areas are difficult environments that are spatially diverse in both horizontal and vertical magnitudes in terms of underground water flow, geological features, and chemical reactions involved (Maître et al. 2003, 2005). Inadequate comprehension of the hydrogeology in riparian areas mostly restricts the quantitative analysis (Correll 1996), while a good understanding is necessary for successful resource management and for protecting and preserving natural environments (Allen et al. 2010; Martínez-Santos et al. 2012).

Although it has been advantageous to develop approaches that focus on the vulnerability of a wetland to climate change, vulnerability could also be examined in an extensive context because climate change is often an additional or aggregate pressure on numerous riparian areas. Vulnerability assessments should hence address the capability of a wetland to

Responsible editor: Marcus Schulz

✉ Jaime Gárfias
jgarfiass@gmail.com

¹ Faculty of Engineering (CIRA), Autonomous University of the State of Mexico, C. P. 50130 Toluca, Mexico

² Department of Geodynamics, University of the Basque Country, 48940 Vitoria-Gasteiz, Basque Country, Spain

³ Institut National de la Recherche Scientifique (INRS-ETE), Québec, QC G1K 9A9, Canada

confront impacts from external water fluxes. In this respect, environmental pollution caused by an increase in the world's population, agricultural fertilizer leakage, and discharge of industrial wastewater have progressively influenced riparian ecosystems. Thus, potential contamination and risk assessment of hazardous chemicals in riparian areas have attracted global debate for reactivity, toxicity, and non-biodegradable properties of these hazardous wastes (Cheng et al. 2015; Liang et al. 2014). Nevertheless, estimation of water resources loss and degradation of the quality of groundwater of these areas is often difficult, demanding management strategies to reverse impacts, as is the case in the wetland-aquifer system of Vitoria-Gasteiz, in which changes in land use and intensification of agriculture have contributed to the disappearance of wetlands some years ago (García-Linares et al. 2003). The impact of wetland alteration and disappearance is particularly difficult to estimate; however, in North America, Australia, New Zealand, and Europe, it is assessed that approximately 50% of some wetland systems have been transformed to other uses (Stratford et al. 2011). Yu et al. (2017) provide a review of mechanisms for land degradation in the Zoige Basin, Tibetan Plateau. Surveys of deteriorated status of China's Coastal Wetlands and the Akgöl Wetland (Turkey) include Cui et al. (2016) and Karakuş et al. (2017). Consequently, establishing the vulnerability of riparian ecosystems to anthropogenic activities, in addition to climate change and other incidents, requires an exhaustive understanding of the complexity of the numerous associated pressures that frequently affect wetland areas.

A variety of techniques can be used to identify the processes controlling environmental contamination to protect sensitive ecosystems, contrasting in their degree of difficulty and their exactitude. Certainly, the incorporation of additional geological and hydrogeological properties of the study area improves the precision and accuracy of any particular method. In this context, the delineation of advective particles is a basic and important component of groundwater protection, in which numerical modeling is applied under steady-state flow conditions, and then backward or forward particle tracking is applied. Other researchers, however, focused on approaches to simulate groundwater flow in the vicinity of wetlands using a 3D transient model (Restrepo et al. 1998), on a transient saturated-unsaturated 2D model (Mansell et al. 2000), on a simulation of contaminant transport to a wetland (Crowe et al. 2004), and on coupling surface water, groundwater processes, and solute transport in coastal wetlands (Yuan et al. 2011). Nevertheless, data uncertainty and scarcity, cost, as well as time of implementation, are often a problem to apply these approaches in a particular hydrological context, use a complex approach that does not guarantee less uncertainty. As pointed out by Paradis et al. (2007), the most appropriate method for groundwater resources protection should be the one that simplifies the flow system to the biggest extent

possible while still conserving its geological and hydrological features. In this sense, as noted by Dong et al. (2013), as a basic and important step, numerical groundwater flow model coupled with particle tracking provides a more scientific method by considering different hydrological settings and time intervals.

Nevertheless, in spite of the strength of the numerical models, few studies have explored the relative expected impact of contaminant sources in hydrological ecosystems and to examine the effectiveness of control measures to protect sensitive ecosystems by means of hydraulic models. Thus, taking into account the strategic significance of groundwater quality deterioration, and in view of the complexity of the hydrological ecosystems and the processes concerned, the main goals of this paper are to evaluate the likely impact of hypothetical spill sites to water quality in the Salburua ecosystem and to analyze the effectiveness of control measures for water protection. The research approach includes a combined use of numerical modeling, advective transport analysis, and pollution assessment aiming to (1) characterize the hydrogeological system and simulate the regional groundwater flow for capture zone delineation in order to establish protection strategies; (2) determine the possible time ranges that point source contamination would take to impact the aquifer below the Salburua ecosystem; and (3) examine how the different control measures affect the global flow dynamics of the travel time-related capture zones. The results not only assess the effectiveness of the research approach proposed in evaluating the dynamic nature of regional wetland systems but also offer insight into some of the factors that constrain the relative expected impact of potential pollution sources on wetland systems in general.

The study area

This study was undertaken in the eastern section of the Vitoria-Gasteiz aquifer, which is located adjacent the city of the same name (Vitoria-Gasteiz, Basque Country) and surrounded by the watershed area of the Zadorra river (Figs. 1 and 2). From the hydrogeological point of view, in this watershed, an aquifer associated with Quaternary stratigraphy exists that constitutes the hydrogeological aquifer system of Vitoria-Gasteiz (EVE 1996). The weather conditions are associated with a continental climate, with significant intra-annual temperature variability fluctuating from less than 0 °C in winter to more than 25 °C in summer and an annual average precipitation of 800 to 850 mm.

Around 75% of the watershed is characterized by intensive agriculture and the rest of the land (25%) is covered by forest. The Salburua wetlands, which are a portion of the open land around Vitoria-Gasteiz and included as a Ramsar wetlands of international significance (Fig. 1), are an area of discharge from the groundwater flow system and are

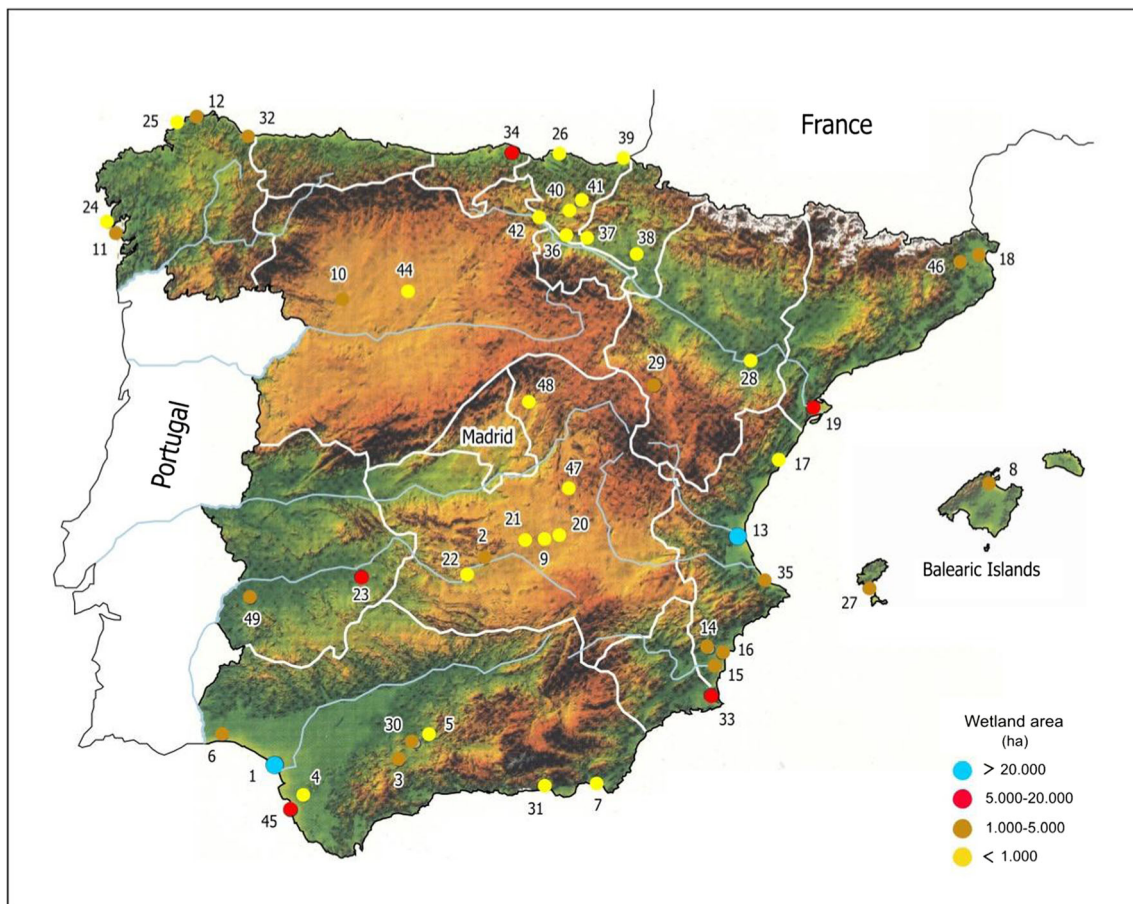


Fig. 1 Location of the Salbarua ecosystem (indicated by 40 in the map) in the context of the Spanish ecosystems included in Ramsar convention (modified from Durán et al. 2004)

fundamentally integrated by two wetlands (Fig. 2): Betoño and Zurbano. In this sense, as stated by the 91/676/CEE European Directive, the Basque Administration of Euskadi recently listed the east sector of this aquifer as a Vulnerable Zone to nitrate pollution. Thus, over the past few years, the natural ecosystem has been reestablished through the abandonment of agricultural practices and closure of the main drainage channels near the wetlands, which has resulted in the elevation of the groundwater levels.

Hydrogeology and groundwater exploitation

Although the main geological characteristics and hydrodynamic properties of the aquifer are not well established, Arrate et al. (1997), García-Linares et al. (2003), Martínez-Santos et al. (2012), and Epelde et al. (2015) have identified some common geological features. The study area exhibits a flat topography with a gentle slope of less than 5% in most parts of the region. The elevation of the watershed varies from 1000 masl in the upstream areas to 510 masl at the outlet of the Salbarua ecosystem, with a mean of 613 masl. Despite of the traditional classification of the regional hydrogeological system used in several

studies (Arrate et al. 1997; García-Linares et al. 2003), the hydrogeological interpretation used in this study relies upon the interaction of the fractured bedrock described by Martínez-Santos et al. (2012). This hydrogeological characterization indicates that the deep groundwater unit is highly dynamic and is cross-connected with the shallow aquifer. Hence, the results of this study suggest that the deeper fractured bedrock system should be included in hydrological analyses along the entire aquifer system. Although hydrogeologists have traditionally considered the alluvial-bedrock interface as an impervious boundary, recent research suggests that a re-evaluation of the conceptual model is needed and offers the basic principles to create a consistent conceptual hydrogeological model of the groundwater flow system in this geological formation. In fact, in some cases, the bedrock could be considered as a stratum of permeable rock; numerous investigations have indicated that the fractured bedrock could contain or transmit groundwater (Haria and Shand 2006; Banks et al. 2009; Abid et al. 2011).

Due to these findings, the main geological units in the study area can be grouped into two hydrogeological units (Figs. 2 and 3), namely alluvial and marl units, according to the hydrostratigraphic schematization criteria outlined by

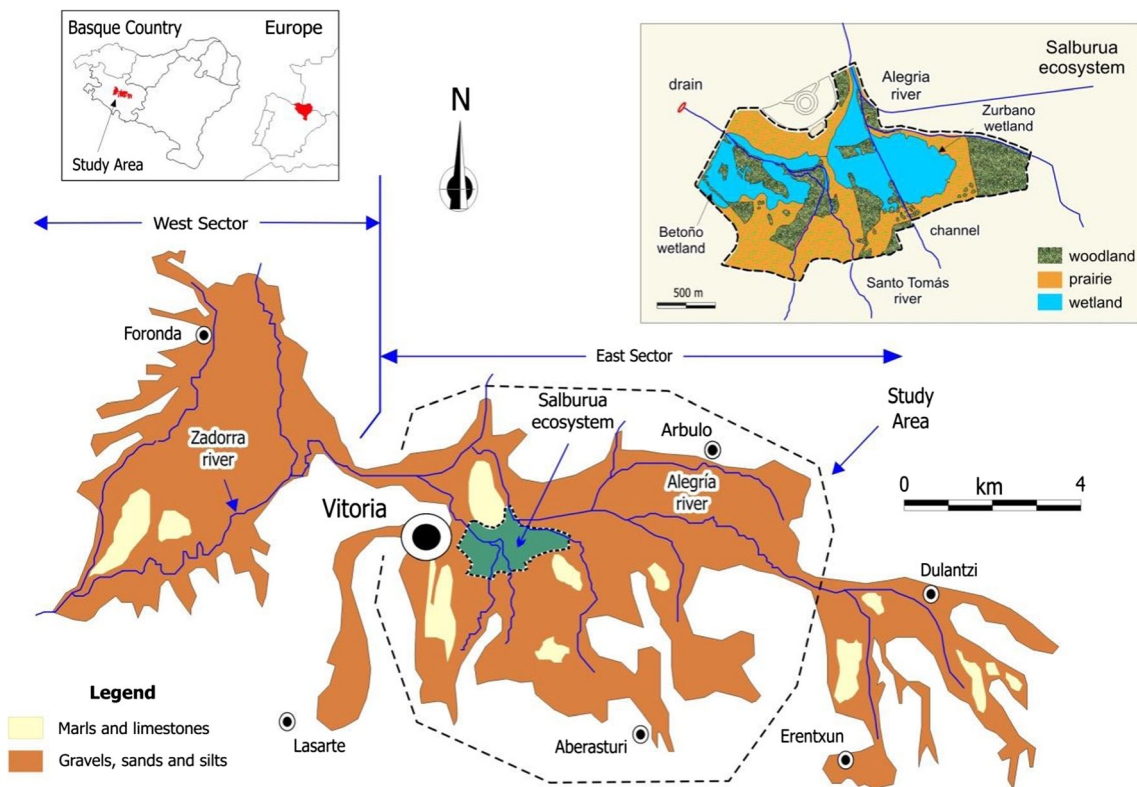


Fig. 2 Location of the study area and general geological map of the quaternary aquifer of Vitoria-Gasteiz (Basque Country, Spain). Also shown is the location of the Salburua ecosystem and the main towns in the area

Martínez-Santos et al. (2012). The first aquifer, cited as the upper aquifer system, is typically unconfined and semi-confined and is characterized predominantly by unconsolidated fluvial and alluvial sediments. The alluvial plain of the watershed is underlain by quaternary materials, which are between 2 and 15 m in thickness, characterized principally by clays and silts with sand and gravel layers and is exploited through shallow wells mainly for agricultural activities. Marl and limestone deposits (calcium carbonate and dolomite composition), with a heterogeneous fracture distribution, make up the stratigraphic sequence of the lower semi-confined aquifer. Hence, the lower aquifer is associated with the marl formation (lower-middle Campanian), which is composed of a sequence of beds of approximately 1000 m thickness, where some fractures have been detected in wells installed at 40 m depth. Likewise, the Urgazi spring, located approximately 4.5 km from the wetlands, is significant in this study for the sulfur concentrations, which may be attributed to highly mineralized rock in a fractured zone in the lower aquifer (Fig. 3). In this context, at the east side of the aquifer of Vitoria-Gasteiz, the alluvial and marl units were considered to constitute one hydraulically connected system. Figure 3 displays the general hydrology system and the hydrogeological characteristics of the east sector of the aquifer system.

Recharge in the aquifer occurs primarily in the topographically high outcrop areas, in which topography and

local relief control the regional groundwater flow. The Alegria River, which moves downstream from east to west of the watershed area, and the Santo Tomás River, which flows from the south to its confluence with the Zadorra River, receive inflow from streams and drainage channels. Rainwater infiltration is the primary source of potential recharge to the Vitoria Gasteiz aquifer system along with percolation from surface water flowing in rivers and streams, whereas water discharge arises through evapotranspiration and through the system of drainage channels and natural streams. Furthermore, recharge by stream run-off of groundwater appears to be a significant component in the natural ecosystem of the study area (Martínez-Santos et al. 2012). In response to the occurrence of very high water periods, groundwater heads can reach the surface in the downstream area, whereas during low water periods, levels can reach a depth of 2 m. In particular, for periods when the groundwater level reaches the maximum height, the natural ecosystem (Betoño and Surbano wetlands) may cover a total of 66 ha, which represent approximately one third of the total area of the Salburua ecosystem. As described previously, groundwater flow in the study area was found to occur in both alluvial formations and in the underlying carbonate rocks. The natural groundwater flow has two patterns: the first is from east to west and the second is from south to north (Fig. 3).

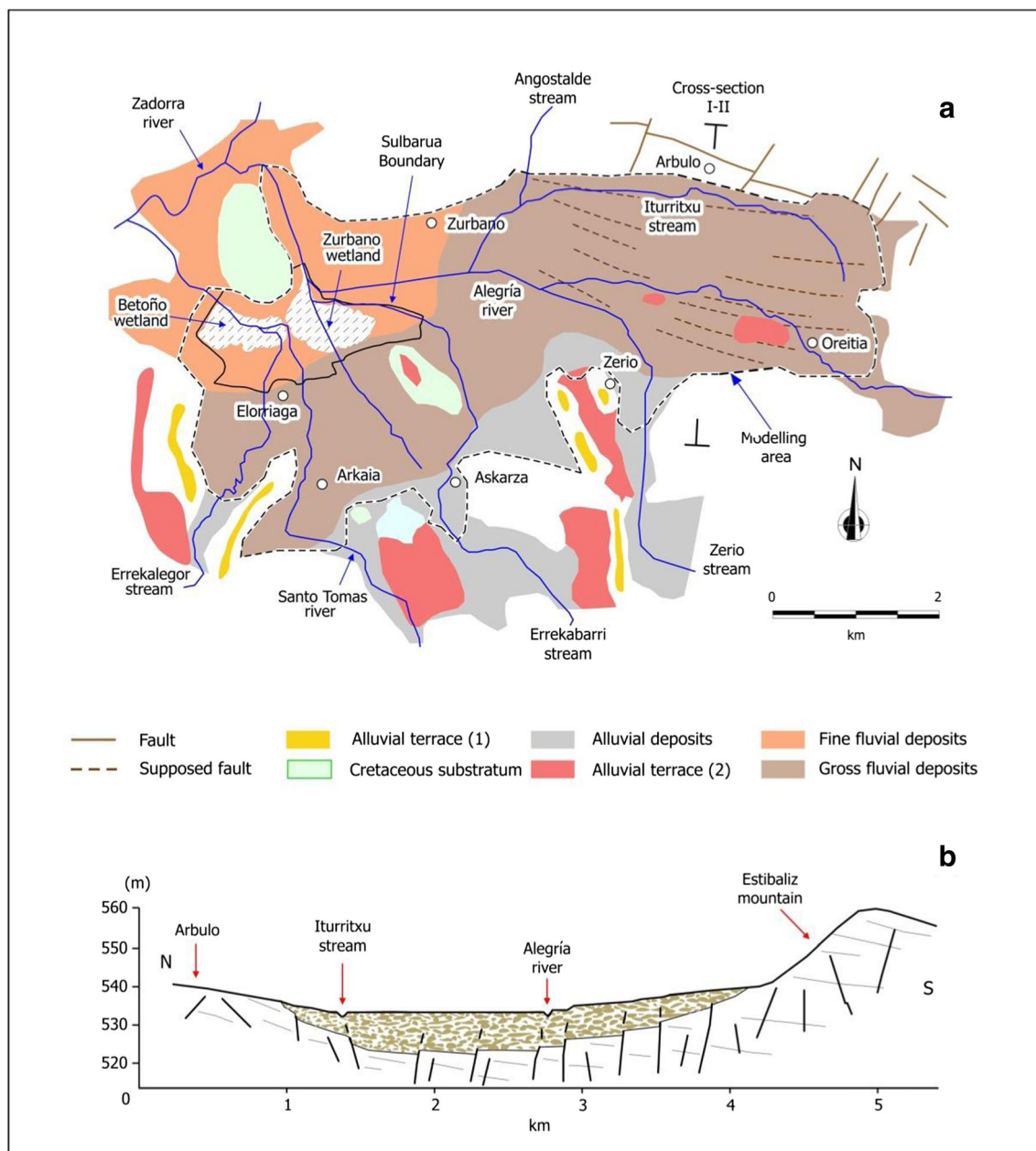


Fig. 3 General hydrology system and hydrogeological characteristics of the east sector of the aquifer of Vitoria-Gasteiz: **a** Conceptual schema of the geological map including the location of the Salbarua

ecosystem and the main towns. Also shown is the boundary of the groundwater flow model; **b** schematic hydrogeological north-south cross section along line I-II shown on Fig. 3a

Impact of land transformations on hydrodynamics of aquifer system

In the 1950s, agricultural activity in the area was characterized by non-irrigated farming, where most of the land was used for cereal crop production. It became apparent, however, that irrigation was needed to achieve higher agricultural yields. As a result, in the subsequent years, new areas for agriculture and water use pressure on groundwater resources have increased, as well as a growth in the demand of fertilizers. As a consequence, water use in irrigated agriculture was extracted from

the underlying aquifer. Under those conditions, during the wet season, recurrent flooding in some areas followed when some streams overflowed, inundating areas due to high water levels that could reach the soil surface. To prevent flooding, a network of drainage channels with a density of 8 km km^{-2} was developed in the east sector of the study area (Arrate et al. 1997). Consequently, a substantial loss of groundwater storage in the aquifer system was created, which was a result of a reduction in the water levels of 1–2.5 m. Because of this, the surface area covered by the local wetlands (Zurbano and Betoño) has been reduced to less than the historical surface

area. Nonetheless, the plans to drain the Zurbano wetland were initiated many centuries ago. In that time, the Wetland Canal was established that was integrated by a system of lateral ditches in this sector. However, in order to recover the riparian area, the Wetland Canal was closed at the end of , which led to a change in water levels and dynamics of the remaining wetlands.

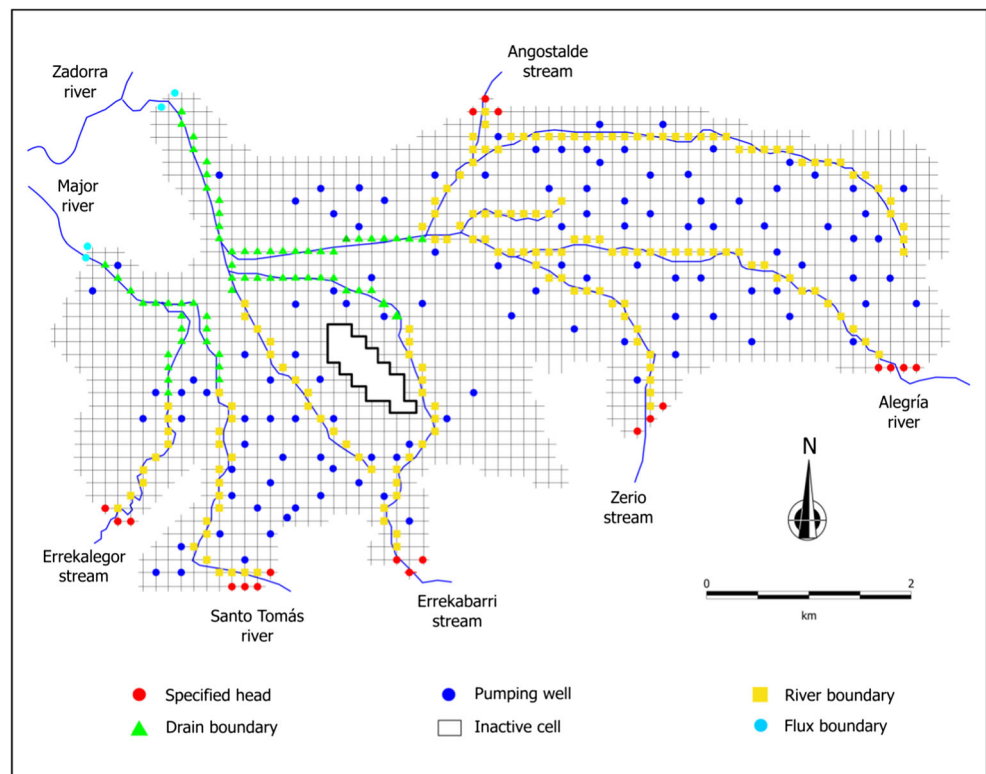
During the 1970s, the Zadorra dam system was constructed in the northern portion of the study area. This dam system is composed of a series of four dams (Ullibarri, Urrunaga, Albina, and Gorbeia), in which the water to supply the Ullibarri dam was taken from the Alegria River that was diverted from its original course through the Alegria Canal (Fig. 2). The modification to the natural river course in the upper watershed affected the recharge rate. To address this impact, the upper part of the watershed area was not included in the study. It is expected that some groundwater flow from the upper to the lower watershed occurs but that it is small considering the limited thickness of the aquifer and the depth of the channel. Likewise in the 1990s, the intensive use of fertilizers and irrigated agriculture resulted in elevated groundwater nitrate concentrations, which regularly exceeded 150–200 mg I⁻¹. An attempt to reestablish the natural ecosystem was made in 1998 when drainage channels were closed and water bodies were built to help store rainwater. The current research was conducted in the eastern sector of the aquifer of

Vitoria-Gasteiz (53 km²). However, it is important to note that accidental spills could severely affect the wetland and its biological activity in this area (Fig. 2).

Simulation of groundwater flow

For the purpose of assessing the vulnerability of the ecosystem effectively, this study applied the VisualMODFLOW 2010.1 (Schlumberger Water Services 2010) to simulate the dynamic groundwater response associated with hypothetical spill sites. A detailed description of the groundwater flow modeling and software use, including the approach used to select MODFLOW inputs, can be found in McDonald and Harbaugh (1988). A three-dimensional, steady-state flow model of the study area was constructed using the aquifer boundary conditions over a local-scale hydrogeological model. A 42 × 74 grid was constructed at a uniform 100-m grid spacing (Fig. 4). This choice of cell size is small enough to adequately represent variations in hydraulic properties and to simulate travel time effects at the scale of interest. The flow system was simulated using two layers with different thicknesses: the upper layer represents the unconfined alluvial aquifer and the lower layer represents the unconfined/semi-confined carbonate-bedrock aquifer. The following material is presented to provide an overview of the flow model on which the particle-tracking analysis is based to assess the vulnerability from potential spill sites.

Fig. 4 Finite-difference mesh in plan view of the flow model and boundary conditions of the groundwater model of the Vitoria-Gasteiz aquifer



Boundary conditions

In order to develop the conceptual model of the aquifer, stratigraphic and hydrogeological studies established by Arrate (1994), in addition to studies developed by Sánchez-Pérez et al. (2003) and García-Linares et al. (2003), were considered according to the basic hydrogeological conditions. These studies indicate that the stratigraphic sequence (thickness) and general features contrast from west to east, as indicated by lateral and vertical facies changes; however, it must be noted that, due to ambiguity in the measured data available, the locations of these boundaries cannot be correctly determined. Likewise, the groundwater flow system assumes that the block sides align with the principal hydraulic conductivity directions. The finite-difference model-grid is oriented in a west-east direction. The hydrological inputs include infiltration, groundwater/surface water interaction, inflow and outflow at boundaries, groundwater extraction, and exfiltration from rivers. A digital elevation model of the topographic contour map of the area was assigned to represent the top elevation of the first layer in the model-grid.

Spatially variable recharge from both infiltration and groundwater/surface water interaction was included in the model, in which a free-surface boundary was assigned to represent the water table dynamics of the upper boundary. The thickness of stratum 1 is highly irregular (upper aquifer system), ranging from 2 m adjacent to the Oreita and Zerio to 15 m in the eastern section of the study area, with an average thickness of around 7 m. The lower boundary of the model is the carbonate-bedrock that underlies the entire study area. The bottom of the model was set at 40 m in the western region and 60 m in the eastern region below the Cretaceous substratum surface to allow for the simulation of the upper part of the Cretaceous substratum. It was assumed that the upper fractured bedrock transmits water into and out of the Vitoria-Gasteiz aquifer, especially beneath the wetland areas where clays and silts with sand layers overlie the fractured bedrock. This depth is believed to represent the base of the local flow system that discharges to the Salburua wetland (Martínez 2008).

The transfer of the hydrological properties to a numerical model needs a reasonable definition of the values used in the model through appropriate boundary conditions. Thus, as illustrated in Fig. 4, according to the geology, hydrogeology, and groundwater heads, as previously described, boundary conditions were determined using the hydrodynamic properties of the aquifer. For this purpose, constant head, constant flux, no-flow, drain, river, and evapotranspiration boundary conditions were used. Thus, specified flow boundaries were assigned to nodes in both model layers at outflow sections of the rivers in the eastern boundary of the model. The specified rates of flow assigned to nodes along these boundaries were

calculated using Darcy's law. Hydraulic conductivities were determined from lithologic descriptions of boreholes and from analysis of aquifer tests. Furthermore, specified-head boundaries were assigned to nodes along the inflow sections of the drainage system of the watershed, in which head values from monitoring wells were taken as reference to assign constant heads. Likewise, a no-flow boundary was applied at the base of the deep semi-confined aquifer as a bottom boundary condition. Taking into consideration the dynamic nature of groundwater, no-flow boundary settings were expected for the remaining aquifer boundaries.

According to observed hydraulic levels in surface water bodies, a specified head boundary was assigned in the model grid affected by the Betoño and Zurbano wetlands in the eastern side of the area. Furthermore, a specified recharge flux boundary was applied at the top of the model, where the infiltration rate was estimated based on meteorological data and soil conditions. The watershed is covered mainly by two rivers, namely the Alegria and the Santo Tomas Rivers, which drain into the Salburua wetland area. The rivers in the study area are treated as mixed boundaries. In this context, river boundary conditions (Cauchy type) are used to simulate the Alegria and Santo Tomas Rivers and their tributaries in the upstream sector of the drainage basin; the required input of riverbed hydraulic conductivity was set uniformly equal to 10 m/day, assuming that this is a reasonable value for sandy-clayey riverbed sediments. In addition, drain boundary conditions are used to simulate tributary streams and the water main network in the downstream sector of the drainage basin; drainbed hydraulic conductivity was chosen according to existing hydrogeological data and adjusted during model calibration. Evapotranspiration was simulated using the evapotranspiration (EVT) package by assuming an extinction depth of 10 m across the basin.

Model variables

Generally, in most aquifer units, it can be expected that changes in hydraulic head or flux and storage of groundwater systems will be controlled by hydraulic properties (e.g., hydraulic conductivity). In this study, the distribution of hydraulic conductivity values used in the upper layer of the model was based on aquifer tests performed in the study area (Ramírez del Pozo 1973; Abalos-Villaro 1989; Arrate 1994). Most of these tests were performed in the south-eastern region and the north-western part. On the basis of evaluation of seven aquifer tests performed in test-well arrays completed in the Quaternary aquifer of Vitoria-Gasteiz, the most representative value of horizontal hydraulic conductivity (K_h) for the productive parts of the wellfield is 3.5×10^{-4} m/s. The range in K_h values determined from the aquifer-test data was 5.8×10^{-5} to 2.3×10^{-4} m/s. Likewise, representative wells were subjected to slug tests in the upper unconfined unit to get initial

approximations of hydraulic parameters using the Bouwer and Rice method (Freeze and Cherry 1979). Results of slug tests show average hydraulic conductivity values ranging from 1.2×10^{-4} to 7×10^{-5} m/s, whereas the maximum and minimum values varied between 6.1×10^{-4} and 3.5×10^{-5} m/s.

For areas in which no aquifer-test data were available, K_h values initially were assigned to the upper model layer by extrapolating values from tested areas based on lithologic description on borehole logs and similarities in geological deposits and then revised by trial-and-error adjustment during model calibration. Areas underlain by fine fluvial deposits with some Cretaceous substratum were assigned a value of 5.8×10^{-5} m/s to the west and the north of the aquifer, whereas areas underlain by coarse fluvial deposits with some alluvial terrace and Cretaceous substratum were assigned a value of 3.5×10^{-4} m/s in the west and middle of the basin. A value of 2.3×10^{-4} m/s was assigned to areas underlain by alluvial deposits and coarse fluvial deposits towards the south and east of the aquifer. Areas underlain by alluvial deposits or alluvial terrace and coarse fluvial deposits were assigned values of 2.9×10^{-4} m/s in the south, and decreasing towards the east part of the aquifer to less than 2.3×10^{-4} m/s, respectively.

Few sets of aquifer-test data are available for the carbonate-bedrock aquifer of Vitoria-Gasteiz. Hence, the magnitude and distribution of K_h values used in the lower model layer were adjusted on a trial-and-error basis during model calibration. K_h values ranged from 1×10^{-4} m/s for an area located east of the Alegria river, where the carbonate bedrock is overlain by fine alluvial deposits, to 5×10^{-4} m/s for the area east of the carbonate-bedrock/alluvial terrace contact, except east of the wetland area where the carbonate-bedrock surface was considered deeper in the conceptual model. This area was assigned a K_h value of 1×10^{-5} m/s. Mohamed et al. (2016) report a K_h ranging from 1×10^{-4} to 1×10^{-5} m/s for pumping tests in an aquifer formed of karstified rocks (United Arab Emirates). The hydraulic conductivity values were interpolated by kriging to generate and acquire continuous layers of the hydraulic conductivity throughout the entire domain of the model grid.

Representative values of horizontal hydraulic conductivity (K_h) are more frequently determined in most aquifer systems than vertical hydraulic conductivity (K_v). In fact, this parameter is one of the most challenging properties of an aquifer to define. In this study, vertical hydraulic conductivity (K_v) values used in the modeling approach were determined through trial-and-error adjustment during calibration. A K_v value of 5.0×10^{-5} m/s was used for alluvial deposits and coarse fluvial deposits. K_v values for alluvial deposits, alluvial terrace, coarse fluvial deposits, and carbonate bedrock were one order of magnitude less than their respective K_h values. According to Carlson (2007), K_h is normally 1 to 2 greater

than K_v ; nevertheless, in overall, vertical anisotropies are slightly larger for hydrogeological systems. The range of these determined K_v values is similar to those determined during model calibration for geological deposits of comparable lithology and origin of an anisotropic aquifer system (Carlson 2007; Mahmoudpour et al. 2016).

Streambed conductance was used in the simulation of leakage from stream nodes in the upstream sector of the drainage basin (Fig. 4). Streambed thickness was assumed to be 30 cm because it is difficult to determine where a streambed ends and an underlying unconsolidated aquifer begins. Three values for streambed conductance, and corresponding values of streambed-hydraulic conductivity (K_{sb}), resulted from trial-and-error adjustment during model calibration and provided the best match between measured and simulated gains and losses along the streams. The values of streambed-hydraulic conductivity, 6.7×10^{-4} , 1.2×10^{-5} , and 2.5×10^{-6} m/s, used to compute these streambed conductance values are within the range of vertical hydraulic conductivity values, 2.9×10^{-4} to 5.8×10^{-6} m/s and close to medium range, 8.1×10^{-5} m/s. Drain boundary conditions are used to simulate tributary streams and the water main network in the downstream sector of the drainage basin (Fig. 4). Thus, drainbed hydraulic conductivities were chosen according to the geological units cut by the stream, or it was set equal to 10 m/day when simulating water main. The initial drainbed hydraulic conductivity values have been subjected to calibration.

The aquifer is principally recharged by infiltration of rainfall received on pervious land surfaces in the drainage basin, with additional contributions from seasonal watercourses and the permanent Alegria and Santo Tomas Rivers. Taking into account a representative mean rainfall (1979–1980) and three infiltration recharge zones identified on the basis of surficial geology of the study area, a soil water mass-balance analysis was applied to obtain initial assessments of expected natural infiltration rates (Swanson 1996; Bradbury et al. 1998). This method uses precipitation measurements, estimates of runoff and evapotranspiration, and soil-moisture storage capacity to estimate groundwater recharge. Based on the daily frequency, precipitation and temperature data sets of the meteorological network were provided by the National Institute of Meteorology (INM), which were analyzed records of stations Aeropuerto 1, Durana, Gazeta, and Arkaute for the period 1970–1995. The distribution of precipitation throughout the year is irregular in the study area. The highest rainfall is concentrated during the period between November and January, even though in some periods, heavy precipitation events occur until May.

In order to achieve a better understanding of the modeling process, a simulation of the aquifer response under dry and wet climatic conditions was established, which is associated to

fluctuations in natural infiltration and groundwater levels. Hence, within the context of the simulation process, groundwater recharge was assessed by supposing that the rainfall record in 1979–1980 (842 mm) was a characteristic baseline (representative mean rainfall), while rainfall in 1988–1989 (507 mm) and 1982–1983 (1140 mm) were considered as dry and wet hydrological years, respectively (October to September). Taking into consideration the soil–water balance from inputs and outputs, infiltration rates for dry and humid years were assessed by multiplying the baseline infiltration year by the relation dry year/baseline and humid year/baseline ratio. Based on the soil–water balance estimates, the relationship among the three hydrological years shows that rainfall infiltration is 40% lower during the dry year than the characteristic baseline year. In contrast, the estimated mean recharge rate for wet years was 1.4 times the 1979–1980 recharge estimates. A similar approach was used by Candela et al. (2014) who established an analysis of extreme dry and wet periods using a groundwater model to estimate the variability of groundwater recharge in the Chari–Logone area of the Lake Chad Basin (Africa).

Taking into consideration the above results and the dry and wet conditions, values of average annual recharge were determined through trial-and-error adjustment during calibration and range from 71 to 162 mm/year. This range is similar to average annual recharge rates obtained by Lu et al. (2011), in which the estimated recharge ranged from 175 mm/year, in areas underlain by the piedmont plain, to 133 mm/year in areas underlain by alluvial, lacustrine plains, and coastal deposits. The lowest estimate of annual recharge rate of 43 to 101 mm/year was assigned in the northwest area of the aquifer since these deposits are underlain by fine fluvial deposits that form a major part of the Salbarua ecosystem. This indicates that these deposits limit infiltration and increase surface runoff in the basin. Likewise, a recharge rate range of 76 to 171 mm/year was assigned in the north and middle of the basin, which consist predominantly of coarse fluvial deposits. In the south and southwest of the study area, which is covered by alluvial and coarse fluvial deposits, a recharge rate of 106 to 239 mm/year was assigned, in which the stratigraphy is characterized by their comparable grain size and high infiltration rate. In fact, the lack of tributary development in this area should be reflected in a greater infiltration rate.

The exploitation of the aquifer system is realized by shallow open wells with very little extraction, in which the land-use type within the study area is covered mostly by surface irrigation field technology. Thus, almost 100% of the total withdrawal rate in the region is used for agricultural purposes. Information for a total of 119 shallow wells with depths from 5 to 20 m was available for this study, of which 19 wells were used as monitoring wells. Based on one hydrological year, pumping rates in m^3/day were estimated based on monthly

pumping rates available for each of the 119 wells to obtain the total groundwater withdrawal. Thus, to estimate the soil water mass-balance analysis, a total pumping rate of $24,192 \text{ m}^3/\text{day}$ was assigned for the 1979–1980 hydrological year (representative baseline withdrawal rate). Likewise, groundwater exploitation patterns for wet and dry hydrological years were determined through trial-and-error adjustment during calibration and range from $19,192 \text{ m}^3/\text{day}$ (wet period) to $28,345 \text{ m}^3/\text{day}$ (dry period). Although any significant changes of the amount of groundwater pumped are planned a long term, it is important to highlight the benefits of a sustainable water balance in the aquifer system. Likewise, the negative side effects of increasing agricultural activities in the future are not expected in the study area.

Model calibration and evaluation of model performance

Due to a lack of temporal coverage of groundwater head data sets throughout the study area, a steady-state groundwater flow model was used to estimate model parameters, as well as to evaluate the response of the aquifer system against various scenarios of climatic regimes. Hence, seasonal or inter-annual responses were not included to assess the groundwater management in the future. In this instance, the steady-state model was calibrated against two different sets of steady-state conditions—one set representing the 1988–1989 hydrological dry year and another set representing the 1982–1983 hydrological wet year. Taking into account the limitations of data imposed by a lack of time series of water levels, the groundwater flow model was calibrated through trial-and-error by matching the simulated and measured water levels over the 19 monitoring wells. It is generally expected that once a satisfactory level of fit between predicted and observed groundwater heads is obtained by a trial-and-error method, simulations achieved by a calibrated model are appropriately reliable to assist as a guide for management policy (Schoups et al. 2006; Mylopoulos et al. 2007; Harou and Lund 2008; Delottier et al. 2017). For this purpose, hydraulic conductivity, hydraulic head boundaries, streambed conductance, and recharge rate data were considered within reasonable ranges to provide a satisfactory match between computed and historical hydraulics heads. Calibration of the steady-state model to two different sets of steady-state field conditions increases the uniqueness of the solution.

Based on the simulations, five statistical measures were used to assess the reliability of the modeling performance. The coefficient of determination (CD) gives the ratio between the scatter of the simulated and observed series. The modeling efficiency (EF) value contrasts the estimated values to the averaged observed values. A negative EF value specifies that the mean value of the measured hydraulic heads would have been an improved prediction than the model. A large

maximum error (ME) value denotes the worst case implementation scenario of the model, while a large root mean square error (RMSE) value indicates how considerable the estimations overestimate or underestimate the measurements. The coefficient of residual mass (CRM) value is a degree of the predisposition of the model to overvalue or undervalue the measurements, in which a negative CRM displays a tendency to overestimate. The maximum value for EF is one, whereas that EF and CRM can be negatives and the lower limit for ME, RMSE, and CD is zero. If all field measured and simulated hydraulic heads achieved by calibration are the same, statistical indices assume values of $ME = 0$, $RMSE = 0$, $CD = 1$, $EF = 1$, $CRM = 0$. In Feng et al. (2011), absolute and square measures of error were used together with the coefficient of determination to evaluate options of integrated water resources management for future development scenarios in an arid region of China.

A sensitivity analysis was performed on hydraulic conductivity of the calibrated model since this parameter had the greatest effect on the model results (Barry et al. 2009; Dong et al. 2013). This parameter was increased and decreased by both 25 and 50% and the global response of simulated hydraulic heads was analyzed. In addition, a sensitivity analysis was also conducted to better quantify the maximum travel time distance sensitivity with respect to hydraulic conductivity. In this context, the hydraulic conductivity values were multiplied by a factor of 1 (calibrated model), 0.25, 0.5, 0.75, 1.25, 1.5, and 1.75 in seven separate simulations and the response of the simulated groundwater flow paths were observed for two travel time intervals (2–5 and 10–20 years) (Fig. 6).

Flow paths and travel times from hypothetical spill sites

The assessment of vulnerability to protect the Salbarua ecosystem from hypothetical spill sites was delineated using the particle tracking approach (Rayne et al. 2001; Barry et al. 2009). In this approach, the velocity flow field is associated with an imaginary particle at an appropriate position and tracked through the groundwater flow pattern at sequential intervals of flow time. As stated by the particle tracking model, hypothetical particles from a given location can be tracked in the down gradient direction (forward approach), as well as in the backward direction to identify potential sources of pollutants (backward approach). Thus, in order to calculate flow paths and travel times, the particle tracking computer code MODPATH was applied to delineate capture zones (Pollock 1994). In order to calculate flow velocities throughout the aquifer, MODPATH is used as a post-processor based on the MODFLOW cell-by-cell mass-balance files. As a result, the particles are tracked through the simulated flow field to calculate time-related capture zones. Thus, as pointed out by Barry et al. (2009), the size and shape of the flow paths are

affected by the hydraulic gradient and flow patterns and the alignment and concentration of fractures.

In order to estimate sequential particle locations, particles were initially set in groups of 15 particles placed close the hypothetical spill sites located at Elorriaga, Arkaia, Askarsa, Zerio, Oreitia, Arbulo, and Zurbano (Fig. 7). As previously mentioned, accidental spills at these towns could severely affect the wetland behavior and its biological activity. Thus, all assigned particles were tracked forward in time from their release until they reached discharge points at the northwest side of the aquifer system. Integrating over all pathways in an area, a vulnerability assessment associated with hypothetical spill sites can be delineated from the associated travel times. Effective porosity (n_e) is the unique parameter that is not included in the calibration of the flow model. Thus, a value of effective porosity of 0.15 was selected for the unconfined alluvial aquifer and 0.05 for the unconfined/semi-confined carbonate-bedrock aquifer. An in-depth analysis of the influence of variability of porosity on time-related capture zones is beyond the scope of this study. In this sense, in order to establish protection zones, the area limited by the Salbarua ecosystem (2.15 km²) was designed as the first-grade protection zone, while the Betoño and Zurbano wetlands were considered as the second-grade protection zone (0.94 km², see Fig. 2). As mentioned previously, the riparian area of the Salbarua ecosystem is essentially formed by two wetlands: Betoño and Zurbano that are located within the first-grade protection zone (Fig. 2). The second-grade protection area is the most sensitive in terms of impacts on quantity and quality of water resources. Under these conditions, flow paths and their travel time map were generated based on the identification of maximum groundwater travel times established for each capture zone (Fig. 6). No degradation of the chemical is occurring and no adsorption of chemical on the geological material is considered making the contaminants conservative and traveling at the same velocity as water (the worst case scenario).

In order to complete this study, the groundwater model and the particle tracking code described earlier were used to formulate and analyze two control measures of potential contamination sources in the vicinity of the Salbarua ecosystem. In this context, the control measures involved the current conditions, the use of a cutoff wall enclosure, and a funnel-and-gate system, which predict changes in response to the proposed control actions. According to previous studies (Rosenberry 2008), the leakage coefficient of the leakage-proof barrier is set to be $19 \times 10^{-9} \text{ m s}^{-1}$ and 1 m thick. Likewise, as stated by Starr and Cherry (1990), the cutoff walls are thick with hydraulic conductivity equal to $1 \times 10^{-8} \text{ m s}^{-1}$, which are reasonable values for conventional soil-bentonite cutoff walls used in the geotechnical construction industry. The hydraulic conductivity of the reactive material in the gate is $1 \times 10^{-4} \text{ m s}^{-1}$. The implemented approach is similar to the work of Zhou et al. (2014), who used a groundwater flow and

transport models to simulate the effects of three control measures in a hazardous waste landfill in China.

Results and discussion

Calibration and simulation results

Before the model was used to evaluate the vulnerability due to hypothetical spill sites at the Salburua ecosystem, calibration was carried out using two different sets of steady-state conditions for groundwater levels. The hydrogeological framework, hydraulic conductivity, constant-head boundaries, streambed conductance, and rainfall infiltration were calibrated to match field measured heads in 19 wells. The study area was distributed into numerous sub-areas based on hydrogeological information, in which the parameters were assumed to be the same for each sub-area. The values used in the model were calibrated conforming to five statistical measures described previously, in which the model parameters were adjusted by using the geological features and the observed groundwater elevations in 1982–1983 (wet hydrological year) and 1988–1989 (dry hydrological year). The purpose of the calibration process is to evaluate different types of model input parameters in an attempt to match the measured hydraulic distribution. The simulated steady-state groundwater heads and comparison between observed and calibrated values are illustrated in Fig. 5. In this schema, simulated heads and observed groundwater levels from 19 monitoring wells indicate comparable hydrodynamic groundwater distribution at the Vitoria-Gasteiz aquifer, which shows that the generalized model of the hydrogeological conditions stated previously are within acceptable limits. In this representation, the groundwater flow direction in the study area was inferred based on hydraulic heads and surface drainage patterns.

As can be seen in Fig. 5a, b, the performance of the steady-state calibration of the developed model for wet and dry periods is almost similar. Overall, the five statistics indicate similar prediction trend with RMSE of 0.63 m for the humid period and RMSE of 0.69 m for the dry period, which suggests that in average, the simulated heads for the humid period are better than for the dry period. The tendency of the predicted groundwater heads to underestimate or overestimate is also comparable in both periods, but this tendency is not very pronounced due to all CRM values are around zero. In addition, there is no substantial difference in calculated CD statistics among the calibrated periods. However, this statistic indicates that the ratio between the scatter of simulated heads and observed heads is slightly higher for the dry period compared to calibrated values of the wet period. In this study, the values of EF vary from 0.99 (wet period) to 0.98 (dry period), showing a good agreement between the predicted and observed groundwater levels (Table 1). The largest maximum

errors (ME) were found for the dry period calibration followed by the wet period calibration. This is due probably to the distribution of hydraulic conductivity values associated to this specific hydrodynamic character in some areas of the aquifer.

Consequently, according to the simulated groundwater heads and the hydrodynamics behavior of the aquifer, it can be seen that there exist two sub-areas that show different degrees of groundwater level errors (Fig. 5). In such a context, one sub-area is located in the upper part (eastern sector) and in the lower part of the aquifer system (western sector). Another sub-area includes the middle and the southwest areas of the Vitoria-Gasteiz aquifer. The ME, RMSE, CD, EF, and CRM between simulated and measured groundwater levels range from 0.74 to 0.96 m, 0.41 to 0.48 m, 0.99 to 0.96, 0.99 to 0.98, and 5×10^{-4} to -3×10^{-4} in the first sub-area. Comparatively, the groundwater model has higher error with ME of 1.57 to 1.75 m, RMSE of 0.81 to 0.86 m, CD of 0.60 to 0.47, EF of 0.69 to 0.32, and CRM of 9×10^{-4} to 3×10^{-4} in the second sub-area (Table 1). This can be attributed to the hydrostratigraphy context and flow conditions in the second sub-area where the control exerted by the geological unit associated with a Cretaceous substratum has a negative effect on the calibration. As a result, the model for the wet period can be used to simulate the probable impacts of potential contamination sources on the water quality of the Salburua ecosystem.

The results of the global sensitivity analysis indicated that the upper aquifer unit exhibits the highest sensitivity to changes, particularly when the value of horizontal hydraulic conductivity was decreased. Similar simulations were also run to test the vertical hydraulic conductivity on the upper unconfined aquifer and the lower aquifer. In both cases, the final modeling had the smallest errors. Hence, the model is most sensitive and has a major impact on groundwater levels in the first hydrogeological unit (upper aquifer). Likewise, Fig. 6 shows results of the sensitivity analysis of the maximum travel time distance (m) with respect to hydraulic conductivity values ranging by three orders of magnitude for two travel times intervals (2–5 and 10–20 years). According to the results shown in Fig. 6, the model was more sensitive to decreases than increases in hydraulic conductivity for the cases considered. Increasing and decreasing the values of the hydraulic conductivity by a multiplier tested the sensitivity of the model to changes in the groundwater flow paths while the other parameters remained constant. Thus, realistic estimates of the hydraulic conductivity distribution for alluvial deposits in these systems are vital for understanding and predicting groundwater-resource management and groundwater protection. Similar calibration processes have been carried out by Barry et al. (2009) and Dong et al. (2013), who demonstrated, based on a groundwater flow model associated to advective transport, that hydraulic conductivity is the most significant parameter in controlling the dimensions of capture zones in aquifer systems.

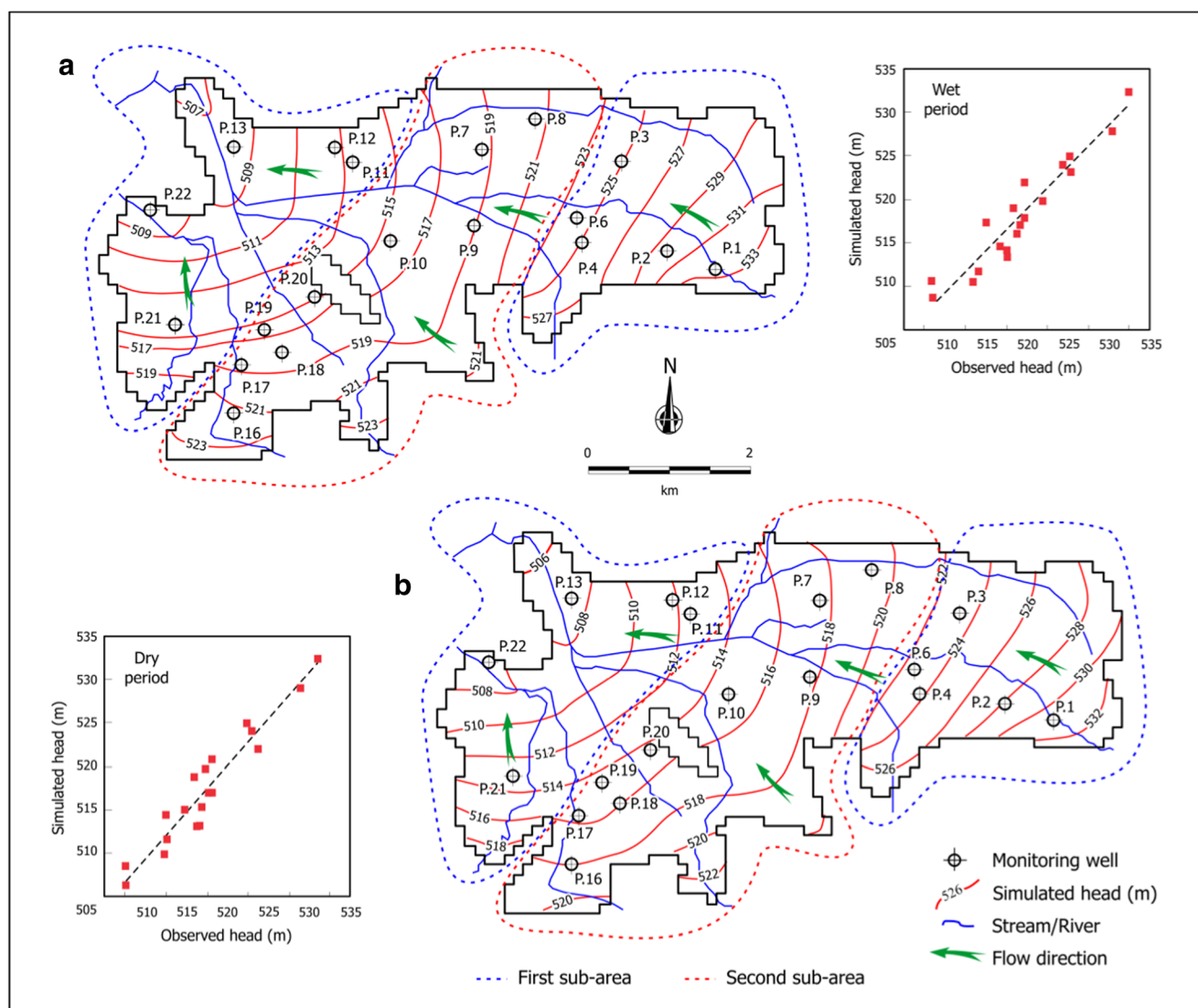


Fig. 5 Simulated steady-state groundwater heads for two conditions: **a** wet period and **b** dry period. Black arrows indicate the groundwater flow direction within the recent alluvium unit. Also shown is the comparison

between observed and simulated groundwater heads for 19 monitoring wells obtained from steady-state calibration

Flow paths and travel time-related capture areas

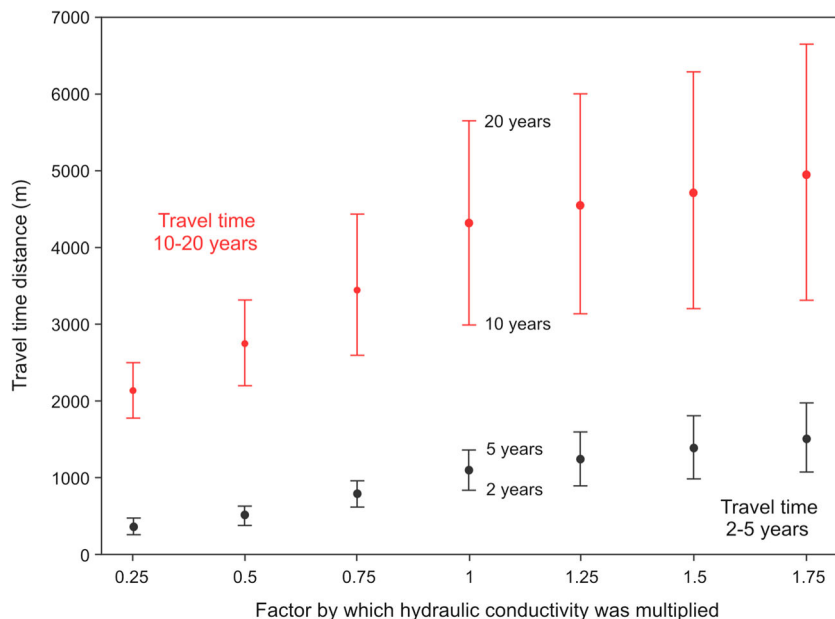
As a result of the calibrated flow model, the average velocity of flow patterns is used to calculate the pathways and transit

Table 1 Performance statistics of the model calibration process for the wet and dry periods

Period	Area	ME	RMSE	CD	EF	CRM
Wet	Total area	1.57	0.63	0.97	0.99	7×10^{-4}
	First sub-area	0.74	0.41	0.99	0.99	5×10^{-4}
	Second sub-area	1.57	0.81	0.60	0.69	9×10^{-4}
Dry	Total area	1.75	0.69	0.94	0.98	1×10^{-6}
	First sub-area	0.96	0.48	0.96	0.98	-3×10^{-4}
	Second sub-area	1.75	0.86	0.47	0.32	3×10^{-3}

times of groundwater particles. In that sense, modeled flow paths were tracked in the forward direction from locations of possible potential sources of pollutants. As illustrated in Fig. 7, predicted flow paths and travel time-related capture zones emanating from hypothetical spill sites reflect the pattern of the groundwater flow system (wet period). Each spill site is located at potential sources of pollutants and then all particles were tracked downward to the ending of the boundary of the aquifer. In this context, as it is indicated in Fig. 7, the first-grade protection zone is the area limited by the Salbarua ecosystem (2.15 km²), while the area limited by the Betoño and Zurbano wetlands is prescribed as part of the second-grade protection zone (0.94 km²). This is particularly essential to protect the riparian wetlands, where protection is considered most important in order to maintain surface and groundwater quality and prevent its further pollution.

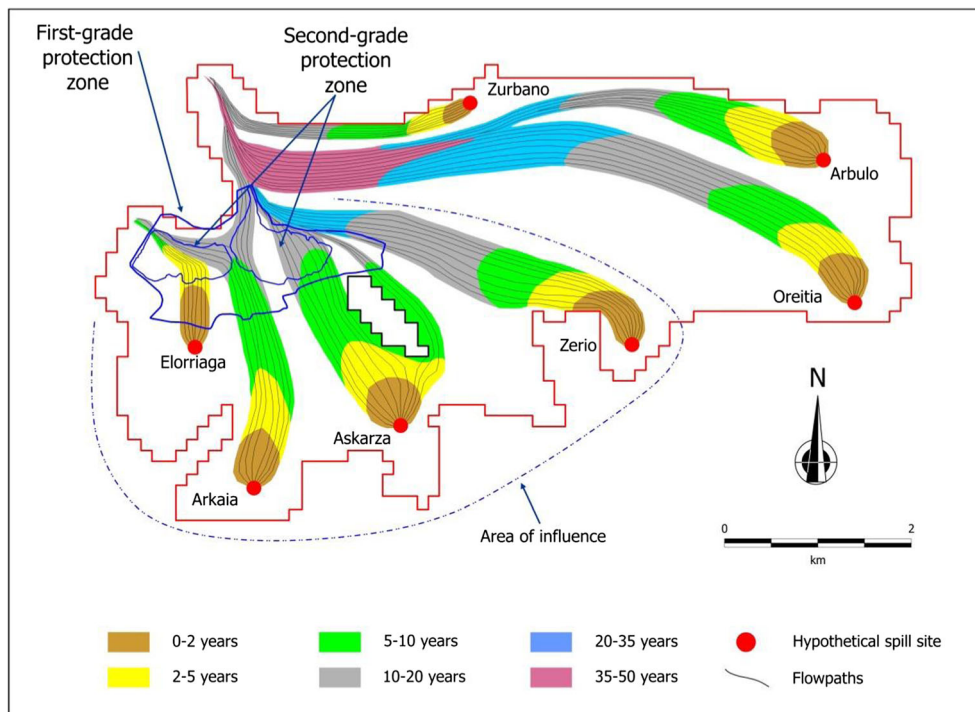
Fig. 6 Sensitivity analysis of the maximum travel time distance (m) with respect to hydraulic conductivity values ranging by three orders of magnitude for two travel time intervals (2–5 and 10–20 years)



The flow paths and discharge points from several of the spill sites vary in response to differences in the simulated steady-state velocity fields affected by the hydrogeological properties of the Vitoria-Gasteiz aquifer. For example, particles entering the flow system at spill sites Elorriaga, Arkaia, and Askarza travel to the first- and second-grade protection zones, whereas some particles released at spill site Askarsa and all particles released at spill site Zerio travel to the second-grade protection zone. In the model simulations, ground-water movement from

the Askarza area to the riparian zone was restricted by the geological unit associated with a Cretaceous substratum. Moreover, particles released at spill sites Oreitia and Arbulo (eastern area) had very long flow paths and travel times, discharging to the boundary of the aquifer downgradient to the Salburua ecosystem. Likewise, particles released at spill site Zurbano (northern area) discharged at the Alegria River without effect on the water quality characteristics and pollution status of the wetland riparian areas.

Fig. 7 Predicted flow paths and travel time-related capture zones emanating from hypothetical spill sites at the potential pollution zones (wet period). Also shown is the location of the first-grade protection zone (Salburua ecosystem) and the second-grade protection zone (Zurbano and Betoño wetlands)



As previously discussed, the resulting particle path distribution determines the travel time-related capture zone for each hypothetical spill site, as shown on Fig. 7, respectively. The capture zones in the northern area were comparatively large and more homogeneously rounded shaped comparative to those of the southern area because of the hydraulic conductivity values in this area and its lesser spatial variability as have been observed previously by Forster et al. (1997) and Barry et al. (2009). In contrast to the northern side of the aquifer, the shapes and sizes of the capture zones in the area of influence of potential sources of pollution originating at Askarza and Zerio reflect the flow pattern in the area. Consequently, the groundwater flow in this area is probably altered by a lower hydraulic gradient than that on the northern area. The extent or dispersion of the resulting capture zones shows bigger and more irregular geometries, indicating that the flow pattern is influenced by diverse flow directions from adjacent areas. The dashed line on Fig. 7 indicates the area of influence of simulated path lines of particles that can potentially pollute the aquatic ecosystem and that may, therefore, continue to pollute downstream groundwater.

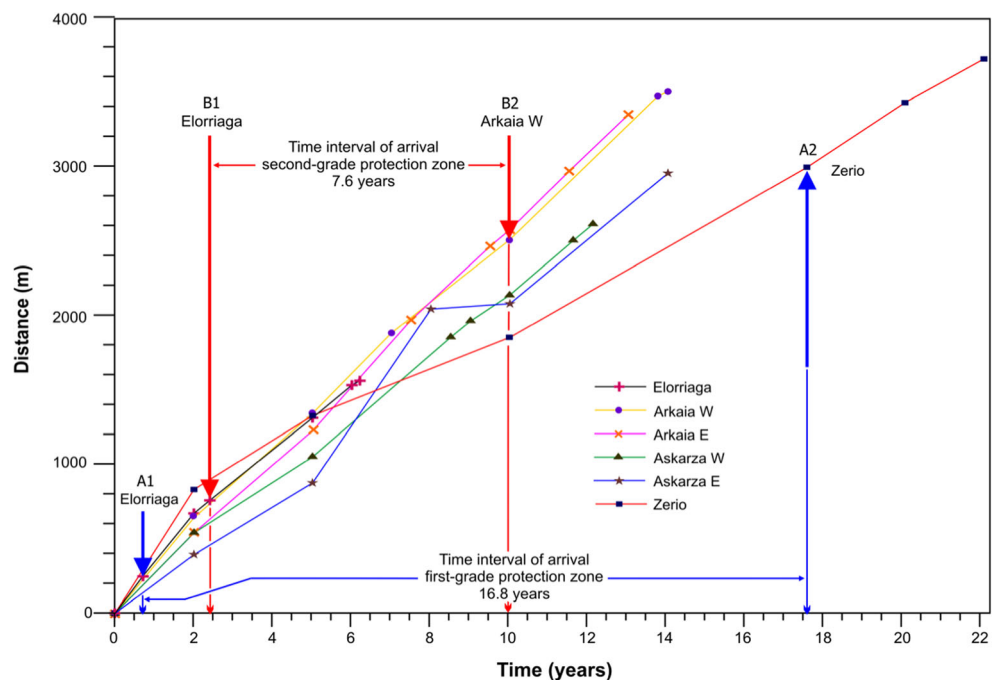
Figure 8 summarizes the computed advective travel times emanating from hypothetical spill sites at the potential pollution zones to the aquatic ecosystem and their exit points. Travel times to the Salburua ecosystem from the hypothetical spill sites differ because of varying flow velocities and distances to the riparian zone. The minimum and maximum travel times to reach the first-grade protection zone (Salburua ecosystem), indicated by A1 and A2 in Fig. 8, were 0.7 years from Elorriaga and 17.5 years from Zerio, respectively. Moreover, the time of travel of the first and the

last particle to reach the second-grade protection zone, indicated by B1 and B2 in Fig. 8, was 2.4 years from Elorriaga and 10 years from Arkaia. Based on the above analysis, it can be seen that the time interval of arrival between the first and the last advective particle is 16.8 years, indicating that the Salburua ecosystem (first-grade protection zone) is affected for all particles at the end of this time interval. Under the conditions simulated, the time interval for the second-grade protection zone is 7.6 years (Betoño and Zurbano wetlands), which indicates that at the end of this time interval, all particles reached the wetland riparian zone. Comparable results have been described by Sahu et al. (2013) in their numerical modeling study of potential groundwater flow patterns from contaminated surface sites for the region of Kolkata, India. Consequently, source contaminant control leading to an effective protection of groundwater resources is of essential importance in order to avoid imminent irremediable environmental deterioration, such as potential impacts on surface and groundwater quality of this sensitive ecosystem.

Control measures to protect the ecosystem

Based on the results of the groundwater flow model and the particle tracking analysis, two control measures of potential sources of pollutants in the vicinity of the Salburua ecosystem were analyzed. Thus, for the purpose of this analysis, the current conditions are considered part of the preexisting condition upon which the other containment alternatives are superimposed. A current condition alternative is required for the analysis of a feasibility study to provide a baseline against

Fig. 8 Simulated advective travel times emanating from hypothetical spill sites at the potential pollution zones (wet period) to the Salburua ecosystem area (first-grade protection zone) and to the Betoño and Zurbano wetland areas (second-grade protection zone). The minimum and maximum travel times to reach the first-grade protection zone (a1 and a2) and the second-grade protection zone (b1 and b2) are also indicated

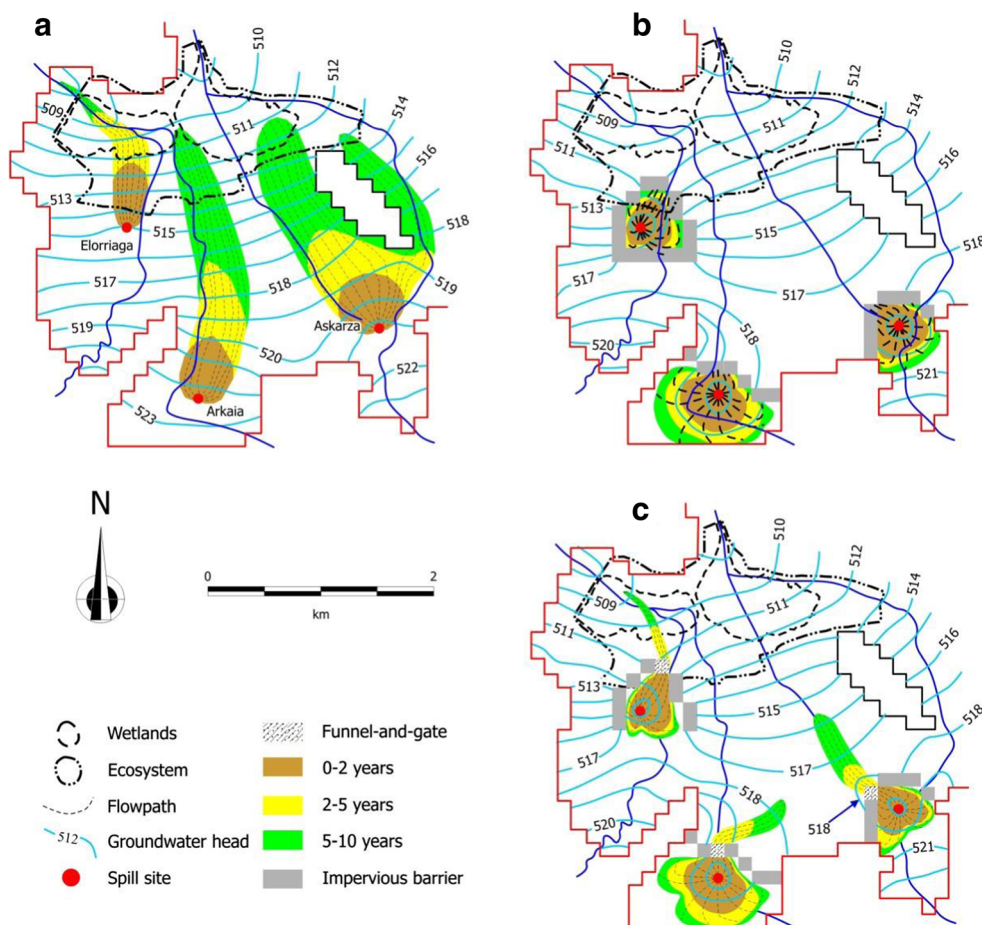


which other alternatives can be evaluated. In this sense, without altering current conditions or adding amendments, this alternative involves no action except the establishment of institutional controls and a water monitoring system. A first attempt was made in the study of Martínez-Santos et al. (2012), in which a monitoring system was installed using piezometers extend over the southern and eastern areas of the Arkaute lagoon at the Victoria-Gasteiz aquifer. The piezometer network was designed for water level measurements to establish groundwater flow direction and to provide adequate spatial coverage of sample collection for the monitoring of water quality. Under this no-action option, contaminated groundwater will continue to discharge into the aquatic ecosystem from hypothetical spill sites, as explained in the previous section (Figs. 8 and 9a). The estimated total costs of this alternative are limited to the capital cost for the establishment of the water-monitoring network and annual costs for operation and maintenance associated with the monitoring program.

Under the second alternative, physical containment measures are designed to isolate the contaminated flow paths and groundwater from the local environment and to minimize any downgradient migration. The depth of the cutoff wall enclosure is selected to reach the bottom part of the upper aquifer and the top part of the bottom aquifer. This set-up is compared

with the situation without changing current conditions or adding modifications (Fig. 9a). As illustrated in Fig. 9b, the leakage-proof barrier can have different effects on the flow path of the advective particles depending on the length and coverage of the enclosure walls. Pankow and Cherry (1996) describe several of these technologies developed for source-zone containment. As exhibited by Fig. 9b, when the depth of the barrier reaches the bottom of the upper aquifer, a closed system is formed and the original modeled flow paths of the advective particle are disconnected, which will lead to the tracked particles to be reduced in the forward direction. Thus, as can be observed in Fig. 9b, inward groundwater flow occurs across the upgradient cutoff wall enclosure. Under these conditions, the potential source zones continue to leak into the lower aquifer and the spill site concentration continues to increase. However, the construction of a cutoff wall enclosure may also facilitate further application of in situ treatment in conjunction with a pump-and-treat system. As a long-term measure, operational costs for these complementary technologies must be minimized to achieve cost efficiency. Bayer et al. (2004) discuss these problems within the framework of optimization of conventional pump-and-treat systems. Therefore, as for continuous point source zone pollution, a leakage-proof barrier is less effective for point-source

Fig. 9 Comparison of the control measures in the critical areas at the aquifer of Vitoria-Gasteiz (wet period): **a** current conditions, **b** cutoff wall enclosure, and **c** funnel-and-gate system



containment, assuming that hydraulic control performance and cost efficiency are the criteria for pollution control effectiveness. The comparison of numerically simulated flow patterns showed that hydraulic barriers could efficiently deflect the flow of potential contaminant sources into targeted zones, leading to apparently optimized systems with insufficient containment or excessive pumping to guarantee pollution control.

As an alternative, the funnel-and-gate system that passively removes the contaminants consists of in situ permeable reactive materials, which eliminates contaminants by adsorption and precipitation or biological mechanisms, is an innovative technology widely accepted for contaminated groundwater treatment (Bayer et al. 2004). In this study, a funnel-and-gate configuration was simulated at each potential pollution site based on the steady-state groundwater flow model. The capture zone of a funnel-and-gate system is analogous to the capture zone of an extraction well and is defined as the region through which water flows before passing through the gate and the region downgradient affected by the water discharge through the gate. Thus, particles were positioned consistently around the hypothetical spill sites and tracked forward for times corresponding to 2, 5, 10 years of travel time for all control measures (Fig. 8). As exhibited by Fig. 9c, the simulations illustrate the effects of the funnel-and-gate geometry on the discharge through the gate, which affects residence time, size, and shape of the capture zone. Comparing Fig. 9a with Fig. 9c, the travel time-related capture zone with the funnel-and-gate system is much smaller than without the control alternative. In this schema, only at the Elorriaga site does the 2-year capture zone reach the boundary of the first-grade protection and the capture zone for 5 years reaches the boundary of the second-grade protection zone. This result is attributed to the fact that, as pointed out by Starr and Cherry (1994), the residence time of the contaminated water in the gate should be as long as possible, so that contaminant concentrations are more attenuated. It should be noted, however, that if the treatment destroyed all of the contaminant sources, there would be no plume exiting the gate. Nevertheless, in this study, modeling of the remediation reactions achieved by the funnel-and-gate system is not considered. Due to these conditions, advective water flow cause formation of flow paths of particles downgradient of the gate. This is a conservative assumption but it provides information to help understand the effectiveness of the treatment system in the gate and represents a worst case scenario.

Summary and conclusions

The groundwater modeling study of the Vitoria-Gasteiz aquifer is used as a tool to analyze the vulnerability of the Salburua ecosystem to likelihood of impact from hypothetical spill sites, as it is expected that anthropogenic pollution and their

potential impact might cause significant environmental degradation that could cause serious damage in the riparian area. The results of the model calibration are internally consistent within an acceptable criterion range, which indicate the relative stability of the simulated hydraulic head distribution. Considering this fact, the model could be applied as a tool for further establishment of a transient groundwater flow model and a contaminant transport model in similar hydrogeological settings. Nonetheless, the groundwater model in the middle sector has larger errors, which could be due to the anisotropy and heterogeneity of the Cretaceous substratum that were not characterized properly when separating the study area into different geological units. The results of the sensitivity analysis indicated that the model is most sensitive and has a major impact on groundwater levels in the first hydrogeological unit (upper aquifer).

The simulations show that pathways of particle tracking originating at potential contaminant sources will tend to migrate downwards towards the sensitive ecosystem, which suggests that the quality of the hydrological ecosystem is likely to deteriorate in the future. Thus, it can be concluded that the first-grade protection zone (Salburua ecosystem) is affected by all advective point pollution sources discharging at Elorriaga, Arkaia, Askarsa, and Zerio in 16.8 years. Likewise, the second-grade protection zone (Betoño and Zurbano wetlands) will be impacted mostly by discharge of all advective flow paths emanating at Elorriaga, Arkaia, and Askarsa in 7.6 years. Moreover, particles released at Oreitia, Arbulo, and Zurbano do not affect the riparian area and discharge downgradient to the Salburua ecosystem. Variation in exit points of particles indicates that the time-related capture area of the individual hypothetical spill sites is affected by changes of the hydraulic gradients. Further modeling studies that combine flow and geochemical processes would improve estimates of the time scale and extent of the contamination threat. Thus, these results can provide a more comprehensive conceptual assessment for the design of protective control systems for riparian ecosystems in Quaternary groundwater aquifers.

Based on the modeling results, the travel time-related capture zone based on a funnel-and-gate system is much smaller than without the control alternative, which indicates that the gate configuration has an effect on capture zone size and shape and on the residence time with a better attenuation level. As expected, advective flow paths at Elorriaga site reach the first-grade protection in 2 years and the second-grade protection zone in 5 years, which validates the reliability of the simulation of the funnel-and-gate system for treating the potential pollution sources. Thus, for the purpose of this analysis, the results show that leakage-proof barrier is less effective for point-source containment, assuming that hydraulic control performance is characterized by insufficient containment or limitations of cost-effectiveness by excessive pumping to

guarantee pollution control. Alternatively, a program to maintain regular groundwater water levels and water quality monitoring of selected wells would both effectively characterize water quality in the aquifer and provide a decision support system to minimize the eventual arrival of contaminants at the riparian ecosystem. Consequently, it is expected that the groundwater flow model could offer an enhanced understanding of the hydrogeological conditions for the design of a more significant and cost-effective strategy to take more effective measures for regulation and conservation.

Acknowledgements The authors would like to acknowledge the support of the National Institute of Meteorology (INM) for providing all data and primary information on the studied Quaternary system. The authors are also grateful to the University of the Basque Country, CONACyT (Consejo Nacional de Ciencia y Tecnología de México), the Consejo Mexiquense de Ciencia y Tecnología (COMECYT), and the Autonomous University of the State of Mexico (UAEM) for supporting this research. We are also immensely grateful to Jennifer Hancox and Amanda Sills for their review and comments on an earlier version of the manuscript. The authors are grateful to the reviewers for their helpful comments and suggestions, which improved the final quality of the paper.

References

- Abalos-Villaro B (1989) Estudio hidrogeológico preliminar del cuaternario de Vitoria. *Bol Geol Min* 100(2):227–247
- Abid K, Zouari K, Dulinski M, Chkir N, Abidi B (2011) Hydrologic and geologic factors controlling groundwater geochemistry in the Turonian aquifer (southern Tunisia). *Hydrogeol J* 19:415–427
- Allen DJ, Darling WG, Gooddy DC, Lapworth DJ, Newell AJ, Williams AT, Allen D, Abesser C (2010) Interaction between groundwater, the hyporheic zone and a chalk stream: a case study from the river Lambourn, UK. *Hydrogeol J* 18:1125–1141
- Arrate I (1994) Estudio hidrogeológico del acuífero cuaternario de Vitoria-Gasteiz (Araba, País Vasco). Thesis (PhD). University of the Basque Country (UPV-EHU)
- Arrate I, Sánchez-Pérez JM, Antigüedad I, Vallecillo MA, Iribar V, Ruiz M (1997) Groundwater pollution in quaternary aquifer of Vitoria-Gasteiz (Basque Country, Spain). *Environ Geol* 30:257–265
- Banks EW, Simmons CT, Love AJ, Cranswick R, Wemer AD, Bestland EA, Wood M, Wilson T (2009) Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). *Hydrogeol J* 17:1969–1989
- Barry F, Ophori D, Hoffman J, Canace R (2009) Groundwater flow and capture zone analysis of the Central Passaic River basin, New Jersey. *Environ Geol* 56:1593–1603
- Bayer P, Finkel M, Teutsch G (2004) Combining pump-and-treat and physical barriers for contaminant plume control. *Ground Water* 42(6):856–867. <https://doi.org/10.1111/j.1745-6584.2004.t014-x>
- Bradbury KR, Rayne TW, Muldoon MA, Roffers PD (1998) Application of a discrete fracture flow model for wellhead protection at Sturgeon Bay, Wisconsin. *Wisconsin Geol Nat Hist Surv Open File Rep*, pp 98–04
- Candela L, Elorza FJ, Tamoh K, Jiménez-Martínez J, Aureli A (2014) Groundwater modelling with limited data sets: the Chari-Logone area (Lake Chad Basin, Chad). *Hydrol Process* 28(11):3714–3727
- Carlson D (2007) Estimate of vertical anisotropy of hydraulic conductivity for northern Louisiana aquifers from grain-size data. Proceedings of Baton Rouge Geological Society's 1st Annual Louisiana Groundwater Symposium, Baton Rouge, Louisiana, vol 1, pp 32–42
- Cey EE, Rudolph DL, Aravena R, Parkin G (1999) Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. *J Contam Hydrol* 37:45–67
- Cheng Q, Wang R, Huang W, Wang W, Li X (2015) Assessment of heavy metal contamination in the sediments from the Yellow River wetland National Nature Reserve (the Sanmenxia section), China. *Environ Sci Pollut Res* 1:1–8
- Correll DL (1996) Buffer zones and water quality protection: general principles. In: Buffer zones: their processes and potential in water protection. Proceedings of the international conference on buffer zones. Samara Publishing Limited, Tresaith, pp 7–20
- Crowe AS, Steven G, Shikaze SG, Carol J, Ptacek CJ (2004) Numerical modelling of groundwater flow and contaminant transport to point Pelee marsh, Ontario, Canada. *Hydrol Process* 18:293–314
- Cui B, He Q, Gu B, Bai J, Liu X (2016) China's coastal wetlands: understanding environmental changes and human impacts for management and conservation. *Wetlands* 36(Suppl 1):S1–S9
- Delottier H, Pryet A, Dupuy A (2017) Why should practitioners be concerned about predictive uncertainty of groundwater management models? *Water Resour Manag* 31(1):61–73
- Dong Y, Xu H, Guomin L (2013) Wellhead protection area delineation using multiple methods: a case study in Beijing. *Environ Earth Sci* 70:481–488
- Durán JJ, García de Domingo A, López-Geta JA, Soria JM (2004) Caracterización geológica e hidrogeológica de los humedales españoles de importancia internacional. In: Proc. XXXIII Congress of IAH-ALHSUD, Zacatecas, Mexico. Conference on groundwater flow understanding from local to regional scales. Zacatecas, México
- Epelde AM, Cerro I, Sánchez-Pérez JM, Sauvage S, Srinivasan R, Antigüedad I (2015) Application of the SWAT model to assess the impact of changes in agricultural management practices on water quality. *Hydrol Sci J* 60(5):825–843
- EVE (1996) Mapa hidrogeológico del País Vasco a escala 1:100.000. Ente Vasco de la Energía – Basque Energy Agency, 377 pp + maps
- Feng S, Huo Z, Kang S, Tang Z, Wang F (2011) Groundwater simulation using a numerical model under different water resources management scenarios in an arid region of China. *Environ Earth Sci* 62:961–971
- Forster CB, Lachmar TE, Oliver DS (1997) Comparison of models for delineating wellhead protection areas in confined to semiconfined aquifers in alluvial basins. *Ground Water* 35(4):689–697
- Freeze RA, Cherry JA (1979) *Groundwater*. Prentice-Hall Canada Inc., Toronto 552 p
- García-Linares C, Martínez-Santos M, Martínez-Bilbao V, Sánchez-Pérez JM, Antigüedad I (2003) Wetland restoration and nitrate reduction: the example of the periurban wetland of Vitoria-Gasteiz (Basque Country, North Spain). *Hydrol Earth Syst Sci* 7(1):109–121
- Gregory SV, Swanson FJ, McKee WA, Cummins KW (1991) An ecosystem perspective of riparian zones. *Bioscience* 41:540–551
- Haria AH, Shand P (2006) Near-stream soil water-groundwater coupling in the headwaters of the Afon Hafren, Wales: implications for surface water quality. *J Hydrol* 331:567–579
- Harou JJ, Lund JR (2008) Representing groundwater in water management models - applications in California. Tech. Rep., California Energy Commission, PIER energy-related environmental research program, CEC-500-2008-092, University of California, Davis, CA, EUA
- Karakuş H, Aydın H, Erdem O (2017) A hydrologic restoration attempt of the dried Akgöl wetland (central Anatolia, Turkey). *Wetlands* 37:837–850
- Liang J, Liu J, Yuan X, Zeng G, Lai X, Li X, Wu H, Yuan Y, Li F (2014) Spatial and temporal variation of heavy metal risk and source in sediments of Dongting Lake wetland, mid-South China. *J Environ Sci Health A* 50(1):100–108

- Lu XH, Jin MG, van Genuchten MT (2011) Groundwater recharge at five representative sites in the Hebei plain, China. *Ground Water* 49(2):286–294
- Mahmoudpour M, Khamehchiyan M, Nikudel MR, Ghassemi MR (2016) Numerical simulation and prediction of regional land subsidence caused by groundwater exploitation in the southwest plain of Tehran, Iran. *J Eng Geol* 201:6–28
- Maître V, Cosandey AC, Desagher E, Parriaux A (2003) Effectiveness of groundwater nitrate removal in a river riparian area: the importance of hydrogeological conditions. *J Hydrol* 278:76–93
- Maître V, Cosandey AC, Parriaux A, Guenat C (2005) Wetlands and aquatic processes. A methodology to estimate the denitrifying capacity of a riparian wetland. *J Environ Qual* 34:707–716
- Mansell RS, Bloom SA, Sun G (2000) A model for wetland hydrology: description and validation. *Soil Sci* 165:384–397
- Martínez M (2008) Dinámica espacio-temporal de la calidad de las aguas de la Zona Vulnerable de Vitoria-Gasteiz (País Vasco). Funcionalidad del Humedal de Salburua en la atenuación de nitratos. Ph.D. thesis, Univ. Basque Country, Spain, 307 p
- Martínez-Santos M, Ruiz-Romera E, Martínez-López M, Antigüedad I (2012) Influence of upwelling on the shallow water chemistry in a small wetland riparian zone (Basque Country). *Appl Geochem* 27: 854–865
- McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference groundwater flow model. Techniques of water-resources investigations of the United States geological survey, book 6, Chapter A1, 586 p
- Mohamed MM, Al-Suwaidi N, Ebraheem A, Al Mulla M (2016) Groundwater modeling as a precursor tool for water resources sustainability in Khatt area, UAE. *Environ Earth Sci* 75(5):400
- Mylopoulos N, Mylopoulos Y, Tolikas D, Veranis N (2007) Groundwater modeling and management in a complex lake-aquifer system. *Water Resour Manag* 21(2):469–494
- Nwankwor GI, Anyaogu CN (2000) Hydrologic characteristics of a small tropical riverine wetland at Ulakwo. Imo state, Nigeria. *Hydrogeol J* 8:646–653
- Pankow JF, Cherry JA (1996) Dense chlorinated solvents and other DNAPLs in groundwater: history, behavior, and remediation. Waterloo Press, Portland, p 522
- Paradis D, Martel R, Karanta G, Lefebvre R, Michaud Y, Therrien R, Nastev M (2007) Comparative study of methods for WHPA delineation. *Ground Water* 45(2):158–167
- Pollock DW (1994) User's guide for MODPATH/MODPATH-PLOT, version 3: a particle tracking post-processing package for MODFLOW, the US: geological survey finite-difference groundwater flow model. US Department of Interior
- Ramírez del Pozo J (1973) Síntesis Geológica de la Provincia de Alava. Edit. Dpto. de Obras Sociales de la Caja Municipal de Ahorros de Alava, Vitoria-Gasteiz, 90 p
- Rayne TW, Bradbury KR, Muldoon MA (2001) Delineation of capture zones for municipal wells in fractured dolomite, Sturgeon Bay, Wisconsin, USA. *Hydrogeol J* 9(5):432–450
- Restrepo JI, Montoya AM, Obeyesekera J (1998) A wetland simulation module for the MODFLOW ground water model. *Ground Water* 36: 764–770
- Rosenberry DO (2008) A seepage meter designed for use in flowing water. *J Hydrol* 359(1–2):118–130
- Sahu P, Michael HA, Voss CI, Sikdar P (2013) Impacts on groundwater recharge areas of megacity pumping: analysis of potential contamination of Kolkata, India, water supply. *Hydrol Sci J* 58(6):1340–1360
- Sánchez-Pérez JM, Antigüedad I, Arrate I, García-Linares C, Morell I (2003) The influence of nitrate leaching through unsaturated soil on groundwater pollution in an agricultural area of the Basque country: a case study. *Sci Total Environ* 317:173–187
- Schlumberger Water Services (2010) Visual MODFLOW, modular three-dimensional finite-difference groundwater flow model, Version 2010.1. Schlumberger Water Services, Waterloo, Ontario, 676 p
- Schoups G, Addams CL, Minjares JL, Gorelick SM (2006) Sustainable conjunctive water management in irrigated agriculture: model formulation and application to the Yaqui Valley, Mexico. *Water Resour Res* 42(10):W10417
- Starr RC and Cherry JA (1990) In situ barriers for groundwater pollution control. Presented at 'Prevention and treatment of soil and groundwater in the petroleum refining and distribution Industry', Montreal, Quebec, October 16 & 17, 1990
- Starr RC, Cherry JA (1994) In situ remediation of contaminated groundwater: the funnel-and-gate-system. *Ground Water* 32:465–476
- Stratford CJ, Acreman MC, Rees HG (2011) A simple method for assessing the vulnerability of wetland ecosystem services. *Hydrol Sci J* 56(8):1485–1500
- Swanson SK (1996) A comparison of two methods used to estimate groundwater recharge in Dane County, Wisconsin. MSc thesis, University of Wisconsin, Madison
- Yu KF, Lehmkühl F, Falk D (2017) Quantifying land degradation in the Zoige Basin, NE Tibetan plateau using satellite remote sensing data. *J Mt Sci* 14(1):77–93. <https://doi.org/10.1007/s11629-016-3929-z>
- Yuan LR, Xin P, Kong J, Li L, Lockington D (2011) A coupled model for simulating surface water and groundwater interactions in coastal wetland. *Hydrol Process* 25:3533–3546
- Zhou Y, Jiang Y, An D, Ma Z, Xi B, Yang Y, Li M, Hao F, Lian X (2014) Simulation on forecast and control for groundwater contamination of hazardous waste landfill. *Environ Earth Sci* 72(10):4097–4104