Significance of enhanced infiltration due to groundwater extraction on the disappearance of a headwater lagoon system: Toluca Basin, Mexico

D. L. Rudolph · R. Sultan · J. Garfias · R. G. McLaren

Abstract Mexico City relies significantly on groundwater resources drawn from the Sistema Lerma well field located in the Toluca Basin, Mexico. Enhanced infiltration caused by groundwater extraction is suspected to be both a prime factor in the disappearance of a lagoon system at the Toluca Basin and a potential risk to long-term groundwater quality. A combined approach of field investigation and numerical modeling was adopted to assess the groundwater-surface water interactions within the lagoon system. Potentiometric data indicate that current downward vertical hydraulic gradients below the lagoon and surrounding wetland area are extremely low suggesting very slow infiltration rates. Geochemical and isotope data from surface water and groundwater sampling also indicate that very little surface water infiltration has occurred. Numerical simulations demonstrate that enhanced surface water infiltration is unlikely to be the primary cause in the significant reduction in size of the lagoon system. Other factors such as modifications to the surface water drainage system and capture of spring flow from the surrounding mountainous regions are likely more significant. Simulations also suggest that contaminants originating in the lagoon system are currently entering nearby production wells although the total contaminant mass flux to the wells is still very low and significantly diluted.

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Résumé La Cité de Mexico dépend significativement des ressources en eau souterraine pompées au site de captages de Sistema Lerma, dans le Bassin de Toluca, à l'Ouest du Bassin de Mexico. L'augmentation de l'infiltration, causée par l'extraction extensive des eaux souterraines, est suspectée d'être à la fois un facteur primaire de la disparition d'un système de lagons en amont de la rivière Lerma au centre de Mexico, et un risque potentiel à long-terme pour la qualité de l'eau souterraine dans la région. Uen approche combinée d'études de terrain et de modélisation numérique a été adoptée pour estimer les interactions entre les eaux de surface et les eaux souterraines, au sein du système de lagons. Les données potentiométriques indiquent que les gradients hydrauliques verticaux descendants sont très bas au niveau des lagons, ce qui suppose un taux d'infiltration faible. Les données géochimiques et isotopiques provenant des eaux de surface et souterraines, indiquent également que peu d'eau de surface s'infiltrent. La simulation numérique démontre quantitativement que l'augmentation de l'infiltration des eaux de surface n'est probablement pas la première cause de réduction des lagons. D'autres facteurs, tels que les modifications du drainage des eaux de surface, l'aménagement en captage des sources situées aux pieds des montagnes environnantes, sont probablement plus importants. Les simulations suggèrent également que les contaminants provenant des lagons se retrouvent également dans les captages les plus proches, bien que le flux total de contaminants entrant dans les captages reste faible. Les volumes d'extraction étant très important ils diluent effectivement les contaminants. Les effets à long-terme de l'extraction critique au niveau des forages de Sistema Lerma et de la dégradation de la qualité des eaux souterraines par les contaminants, nécessite une grande attention pour le futur.

Resumen La Ciudad de México depende significativamente de los recursos de aguas subterráneas obtenidos del campo de pozos Sistema Lerma ubicado en la Cuenca Toluca, oeste de la Cuenca de México. Se sospecha que la infiltración estimulada causada por extracción intensiva de aguas subterráneas es un factor principal en la desaparición de un sistema de lagunas en la cabeceras del Río Lerma en el centro de México y un riesgo potencial para la calidad de aguas subterráneas a largo plazo en la región. Se adoptó un enfoque combinado de investigación de campo

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y modelizado numérico para evaluar las interacciones de agua superficial-agua subterránea dentro del sistema de lagunas. Datos potenciométricos indican que los gradientes hidráulicos verticales descendentes actuales, ubicados por debajo de la laguna y vecina área de humedales, son extremadamente bajos sugiriendo ritmos de infiltración muy lentos. Datos geoquímicos e isotópicos provenientes del muestreo de agua superficial y subterránea también indican que ha ocurrido muy poca infiltración de agua superficial. Las simulaciones numéricas demuestran cuantitativamente que no es probable que la infiltración estimulada de agua superficial sea la causa principal en la reducción significativa del tamaño del sistema de lagunas en la cabecera. Otros factores tal como modificaciones al sistema superficial de drenaje de agua y captura de flujo de manantial en las regiones montañosas vecinas son probablemente más significativos. Las simulaciones también sugieren que los contaminantes que se originan en el sistema de lagunas están actualmente ingresando a pozos de producción cercanos aunque el flujo de masa contaminante total a los pozos es aún muy bajo y diluido significativamente en los volúmenes grandes de extracción. La magnitud de la amenaza a largo plazo a la calidad del agua subterránea en los pozos de producción Sistema Lerma proveniente de contaminantes infiltrados es una preocupación y amerita estudios futuros.

Keywords Headwaters · Lagoon · Wetlands · Enhanced infiltration · Groundwater supply · Contamination · Toluca Basin · Mexico City

Introduction

At an international scale, the disappearance of freshwater lagoons and wetland systems has become a significant concern. The factors influencing this phenomenon are varied and may include, for example, climate change, urbanization and the depletion of recharge water, both surface and groundwater. In many parts of the world, important wetland systems situated near areas of significant groundwater resource development have been observed to be decreasing in lateral extent, presumably as a result of extensive groundwater extraction. The complex interactions between the groundwater and surface water systems are not yet well understood and are of critical importance in the development of appropriate wetland restoration approaches. Several dramatic cases have been documented in Mexico near large urban centers, one of which is the focus of this current study.

The sustained growth of Mexico City and surrounding regions has depended on the continuous development of both local and regional water resources for industrial and domestic use. Groundwater, being the primary source of potable water in the region, has been the focus of many studies (Rudolph et al. 1991; Ortega et al. 1993; Legorreta 1997; DGCOH 1997). Within Mexico City, the dense population of over 18 million in an area of 400 km^2, has placed heavy stress on the water sources (Legorreta 1997). Depletion of groundwater resources within the Basin of Mexico has forced this megacity to look to neighboring basins to meet its growing water demands.

Since 1942, the Lerma River Basin within the State of Mexico, approximately 100 km to the west of the Valley of Mexico, has been providing potable water to Mexico City (Fig. 1; Sabalcagaray 1981; UAEM 1993). Initially, local springs in the mountains surrounding the Lerma River Basin were tapped and in 1951, the Sistema Lerma, an extensive groundwater extraction and transfer system, began operation (UAEM 1993). The series of 236 water wells associated with the Sistema Lerma (Fig. 2) currently provides approximately 4.5 m^3/s of water to Mexico City (approximately 7% of the total demand; Legorreta 1997). The majority of the production wells are completed as deep (200–300 m) bedrock wells with long screened sections drawing water from the intermingled basalt flows and the volcanoclastic sediments associated with the Sierra de Las Cruces mountains. This continuous line of wells captures groundwater from both the adjacent mountainous area and from beneath the Toluca Basin, and effectively forms a linear drain or sink along the eastern boundary of the Basin.

In addition, within the Toluca Basin itself a significant water demand from extensive agricultural and industrial activity exists. For example, the newly developed Industrial Corridor, located near the city of Toluca (Fig. 1), consists of industry displaced from the Basin of Mexico after the destructive 1985 earthquake, which severely impacted Mexico City. This industrial area relies almost entirely on groundwater resources within the Lerma Basin, which is currently the fastest developing urban and industrial area in Mexico.

The extensive extraction of groundwater in the Toluca Basin has lowered the water table, changed regional groundwater flow patterns and reversed vertical hydraulic gradients in the valley floor sediments in some regions. In addition, springs in the surrounding mountainous regions have progressively disappeared over time (UAEM 1993). The extreme southern end of the Basin, near the Sistema Lerma wells, contains a large wetland area, including several surface water bodies or lagoons, which form the headwaters of the Lerma River. Since 1943, the surface water area has decreased from 10,700 to 3,200 ha (UAEM 1993). Currently, only the southernmost feature, Laguna Almoloya, remains (Figs. 1 and 2). This water body is also the receptor of direct discharges of untreated wastewaters from surrounding towns and industries. The water quality in Laguna Almoloya and ultimately the Lerma River, has subsequently decreased significantly over time (UAEM 1993). Contamination of Laguna Almoloya also poses a serious threat to the groundwater quality in the Sistema Lerma wells.

The fate of the lagoon and wetland system is of critical concern to municipal authorities considering its importance as a headwaters region and ecological habitat (Gárfias 1997; Diez 1998). It is anticipated that massive groundwater extraction within the Toluca Basin may be contributing to the slow disappearance of surface water bodies and wetlands that has been documented in the southern part

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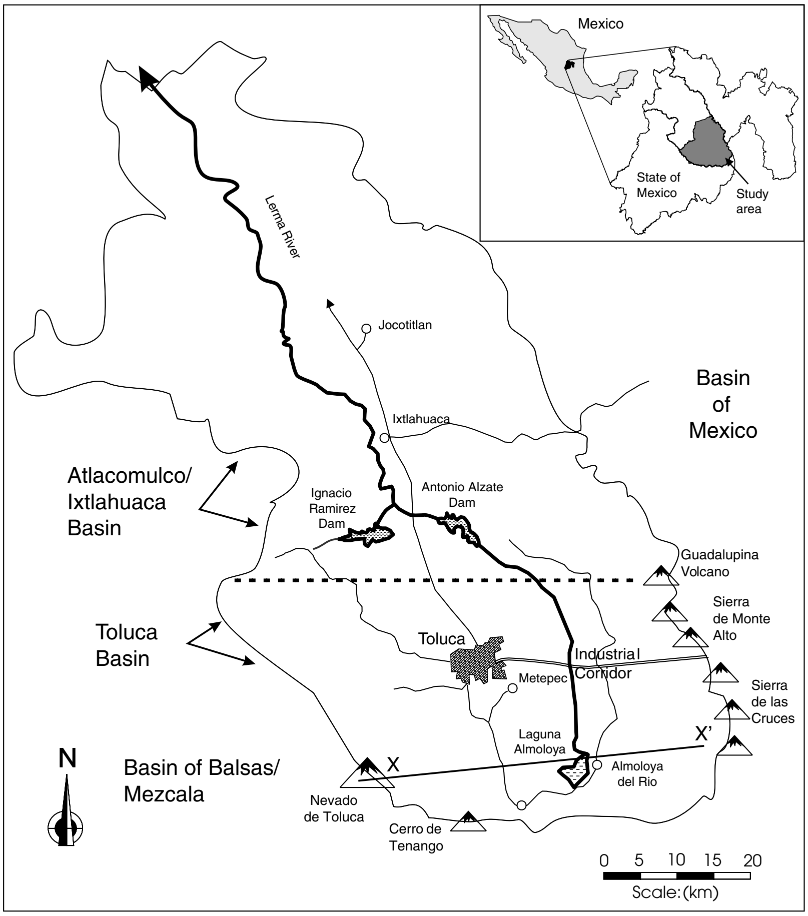

Fig. 1 The Upper Lerma River Basin extent showing the division between the Toluca Basin to the south and the Atlacomulco/Ixtlahuaca Basin to the north. Also shown are the major volcanoes, mountain ranges and the surrounding basins along with the location of the generalized geologic cross-section X–X′ shown in Fig. 3

of the basin over several decades (UAEM 1993; CNA 1996a; Diez 1998). In particular, the interbasin transfer of groundwater from the Sistema Lerma production wells is suspected to be linked to the progressive shrinkage of the adjacent lagoon system (Fig. 2; UAEM 1993; Diez 1998). However, the hydrologic phenomena responsible for the progressive disappearance of the lagoon-wetland system are not well understood but may include modifications in the surface water drainage, capturing of spring waters by production wells and decreases in groundwater discharge to the headwater area as a result of hydraulic gradient reversals beneath the valley floor.

Considering the combined potential impacts on the future fate of the lagoon system from enhanced infiltration and the threat to the groundwater quality in the critical Sistema Lerma wells as contaminants migrate from Laguna Almoloya to the well intakes, the nature of the transient water flux at the base of the Laguna was chosen as the focus of the current research. The first objective of the work was to characterize the groundwater-surface water interactions in the vicinity of the Laguna Almoloya in order to assess the impacts of pumping from the Sistema Lerma wells. This component of the study focused on the quantification of water flux at the base of the lake through a combination of field investigations and numerical analysis. A second objective involved assessing the potential for contaminant movement from the surface waters to underlying aquifers and, ultimately, the deep production wells of the Sistema Lerma system. Based on historical information and the data collected during the course of this project, predictive simulations were developed to evaluate the risk of groundwater quality impacts from infiltrating surface waters beneath the Laguna Almoloya. The results not only demonstrate the utility of various investigative approaches in evaluating the dynamic nature of groundwater-surface water interactions in regional wetland systems but also provide insight into some of the factors that control the impacts of groundwater extraction on wetland systems in general.

Geographic setting

The Lerma River Basin is located in the central portion of the State of Mexico at an elevation of approximately 2,580 masl (DGCOH 1992). The basin has been subdivided into the Toluca Basin to the south, and the Atlacomulco/Ixtlahuaca Basin to the north (Fig. 1). These two basins are geomorphologically separated by a topographic high that runs east-west just North of Toluca, although the Lerma River, originating in the south, traverses both basins.

The Toluca Basin, also referred to as the Upper Lerma Basin, is separated from other neighbouring basins by a series of physiographic features. To the east, lies the

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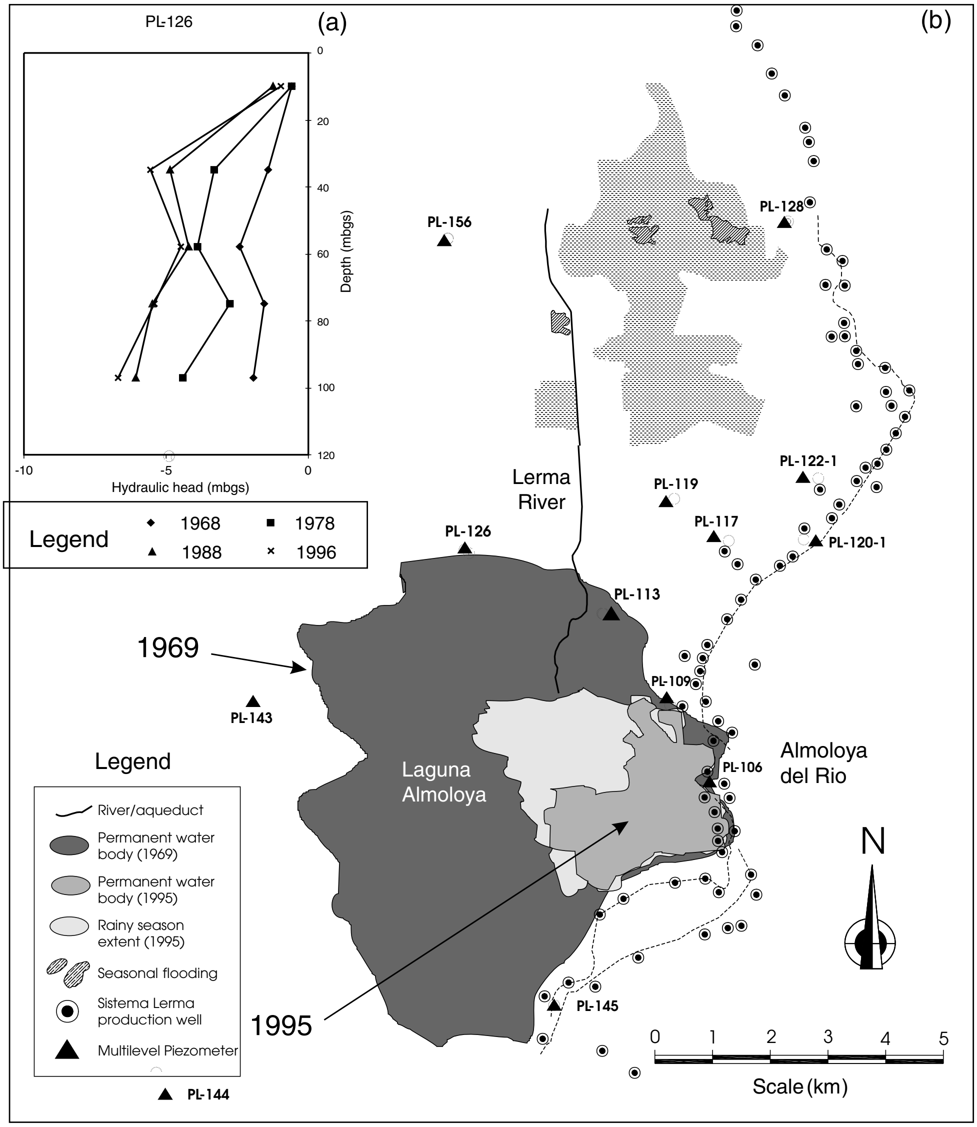
Fig. 2 **a** Historical hydraulic head profile recorded in CNA well PL-126. **b** Lateral extent of the Laguna Almoloya in 1969 and in 1995. Also shown is the seasonal flooding that occurs during the rainy season (May to October) each year. The location of several CNA multilevel monitoring wells and the Sistema Lerma wells are also shown (modified from DGCOH 1997; CNA 1996a; Diez 1998)



Sierra de las Cruces mountain chain, a complex system of mountains rising to an elevation of over 3,700 masl (Gobierno del Estado de México 1997). These mountains run in a northwest-southeast direction and separate the Lerma River Basin from the Basin of Mexico to the east. Along the southern and western boundaries of the basin, lie the volcanoes Nevado de Toluca and Cerro de Tenango that divide the Toluca Basin and the Basin of Balsas-Mezcala (Gobierno del Estado de México 1997; DGCOH 1997; Fig. 1).

The rainy season generally occurs during the months of April to October. The basin interior receives an average of 690 mm of precipitation annually (Lesser y Asociados 1992). The higher altitudes receive larger amounts of rain, in the range of 1,200 mm/yr (Gobierno del Estado de México 1997), and during the winter months, precipitation may fall as snow on the Nevado de Toluca volcano (DGCOH 1997). Annual precipitation cycles and amounts in the basin have been relatively constant since the first year of available data in 1942 (Lesser y Asociados 1992).

Regional hydrology

Hydrogeology and groundwater exploitation

The regional hydrogeologic system within the Toluca Basin is generally considered to contain two main aquifer units. The semi-confined Lower aquifer consists of a heterogeneous mixture of volcanoclastic deposits associated with the laterally extensive Tarango Formation intermingled with lava flows from the surrounding mountains (Fig. 3) and ranges in thickness from 100–400 m (CNA 1996b). A majority of the production wells are completed within this aquifer (DGCOH 1992). The second main aquifer unit, referred to as the Upper aquifer, is locally semi-confined and unconfined and consists primarily of heterogeneous alluvial sediments, intermittently separated from the Lower aquifer by low permeability organic clay materials (CNA 1996b). The Upper aquifer unit is overlain and occasionally interlayered with a discontinuous lacustrine clay deposit (Fig. 3; CNA 1996a). This upper alluvial and lacustrine deposit ranges from nonexistent along the basin boundaries

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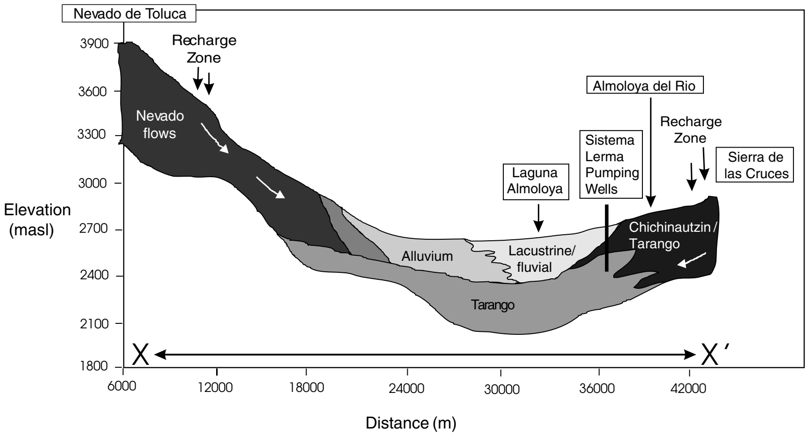

Fig. 3 General basin geology: west-east cross-section (*X–X′*) (Fig. 1) through the southern Toluca Basin from Nevado de Toluca volcano to the foothills of the Sierra de las Cruces mountains. The primary recharge areas and general direction of groundwater flow are also indicated in the diagram. (Modified from CNA 1996b)

to over 100 m thick near the centre of the basin and is used locally for shallow groundwater supplies. Primary recharge to the regional aquifer system is believed to be through the permeable volcanic mountains that flank the basin (Fig. 3) (DGCOH 1992; CNA 1996a, 1996b).

Since the early 1950s, the regional groundwater flow field has been significantly affected by local groundwater extraction with the largest impacts associated with the Sistema Lerma well system (Fig. 2), which has drawn flow towards the eastern flanks of the basin (CNA 1997).

Historically, piezometric levels throughout the Lerma River Basin were observed to be near ground surface with local springs encountered in the flanks of the surrounding mountains and at the edge of the basin (Lesser y Asociados 1992). Currently, regional static water levels in the lower aquifer unit are reported to be between 10 and 30 m below ground surface throughout much of the southern part of the basin, with the deepest water levels occurring in the vicinity of the Sistema Lerma wells (DGCOH 1992; Lesser y Asociados 1992).

In 1968, the Gerencia Regional de Aguas del Valle de México installed a series of multilevel monitoring wells throughout the southern Toluca Basin several of which are indicated on Fig. 2. These wells consisted of discrete monitoring points (normally 4 or 5) ranging in depth from about 10 to over 180 m in some locations. Data collected from these monitoring wells is reported and analyzed in CNA (1996a) and CNA (1997) and provide historical information on the groundwater levels in the hydrostratigraphic sequence. Several of the CNA multilevel wells are situated in the immediate vicinity of the current study area as shown on Fig. 4 (PL-126, 113, 109 and 106). Data from the majority of the multilevel piezometric records indicate that hydraulic head levels have been decreasing since the time of installation. Although the vertical hydraulic gradients in the near-surface sediments have remained very small, hydraulic gradients appear to have begun to reverse from slightly upward to downward in the deeper parts of the hydrostratigraphic sequence (CNA 1996a; Fig. 2a).

Surface water hydrology

Historically, three large surface water bodies existed in the Toluca Basin covering an area of 10,700 ha in 1943 (UAEM 1993). Today, the only remaining water body is Laguna Almoloya, with an extent of 3,200 ha (Fig. 2b; UAEM 1993). The lagoon and surrounding wetlands form the headwaters of the Lerma River. Prior to 1940, large springs in the foothill region around the eastern and southern boundaries of the lakes were a continuous source of recharge to lakes and wetlands. In 1942, much of the spring flow was diverted to Mexico City to augment the potable supply (Vasquez 1987). Over time, spring flow has progressively decreased and is now essentially nonexistent, likely due to a regional lowering of the water table by groundwater extraction from the Sistema Lerma wells. Decreased inflow to the wetlands from the springs is likely one of the main causes of the observed desiccation in the region (Sabalcagaray 1981; Vasquez 1987).

In 1975, berms were constructed within the Laguna Almoloya to restrict surface water outflow from the water body and to maintain the volume of water in the wetland (Diez 1998). They have helped to maintain the annual baseflow in the Lerma River and have minimized the potential impacts of flooding. Laguna Almoloya receives wastewater discharge from surrounding communities, which has led to water quality degradation in the Laguna itself and the Lerma River (DGCOH 1992; UAEM 1993).

Materials and methods

The research investigation involved three main components. First, historical information including reports by government agencies and consultants were collected and reviewed to provided valuable physical data on the regional hydrogeologic setting and groundwater use. Second, a field program involving monitoring well installation, sediment characterization, hydrologic monitoring and surface water and groundwater sampling was conducted in the shallow subsurface environment in the vicinity of

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Laguna Almoloya. These data were then used to develop a conceptual hydrogeologic model of the upper subsurface in the southern part of the Toluca Basin. Finally, a groundwater flow and transport model was used to conduct a quantitative assessment of the groundwater-surface water interactions in the vicinity of the Laguna and to investigate potential long-term impacts of infiltrating Laguna water on the quality of the Sistema Lerma well water.

Monitoring well installation and sediment sampling

In order to measure vertical variations in piezometric levels, estimate hydraulic properties of the subsurface materials and collect groundwater samples for geochemical and isotopic analysis, shallow monitoring well clusters were installed at four sites in and around Laguna Almoloya. The first was located within the Laguna interior (Site A), the second on the eastern shoreline (Site B), a third at the outlet of the Laguna water as it flows into the Lerma River (Site C), and a fourth on the western shoreline of the lake (Site D; Fig. 4).

At Sites A and B, a hollow stem auger drill rig was used to install the monitoring wells and to collect core and auger flight samples to define the local near-surface stratigraphy and to permit hydraulic parameter estimation through laboratory testing. Following the sediment sampling process, wells were installed to 28 m and 17 m depths at Sites A and B, respectively.

A drive-point method, which had successfully been applied in several similar locations within the Basin of Mexico (Rudolph et al. 1991; Ortega et al. 1999), was also used to install shallow wells at the four sites. In total, 11 drive-point wells were installed; four at Site A at depths ranging from 7 to 17.6 m, two at Site B (4.4 and 9.4 m), three at Site C (5 m, 10.1 m and 17.3 m) and two at Site D (3.8 m and 12.3 m). All wells were level surveyed and the bathymetry of the Laguna Almoloya was determined at several locations through sounding measurements.

Stratigraphy and hydraulic parameter estimation

The near-surface stratigraphic sequence in the vicinity of Laguna Almoloya was constructed by inspecting core samples and cuttings collected during drilling. Borehole logs from the Sistema Lerma production wells and from the CNA multilevel wells located within the study area were used to characterize the deeper geologic environment. The CNA logs provided detailed point-source stratigraphic information, which supported an assessment of the lateral continuity of the main hydrostratigraphic units.

Hydraulic conductivity was estimated through grain size analysis of sediment samples using the empirical rela-

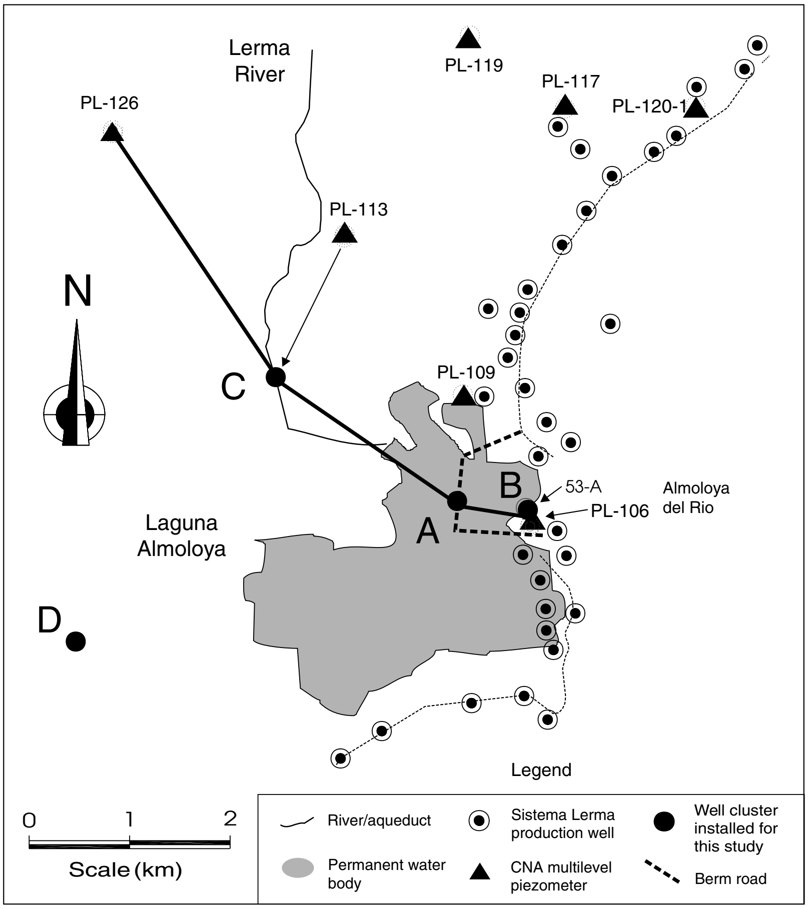

Fig. 4 Site map showing the location of well clusters A, B, C, D, CNA multilevel piezometers and Sistema Lerma production wells in the vicinity of Laguna Almoloya. Also shown is the location of the hydrostratigraphic cross-section below the laguna used for numerical simulation (modified from DGCOH 1997 and CNA 1996a)

tionships of Slichter (1899) and Sauerbrei (Vukovic and Soro 1992) and through falling-head permeameter testing. Single-well response tests were conducted on all monitoring wells and analyzed using the Hvorslev (1951) method to estimate the hydraulic conductivity of the materials in which the screens were positioned.

In addition, groundwater levels were measured in each of the installed wells in May 1999, August 1999 and June 2000, which permitted some insight into the seasonal variations in groundwater levels.

Geochemical and isotope analysis

Water samples were collected from all installed wells, selected Sistema Lerma production wells, and surface water bodies including the Laguna Almoloya and the Lerma River. Geochemical analysis included the anions chloride, sulfate, nitrate, nitrite, bicarbonate and bromide and the cations calcium, magnesium, sodium, iron, arsenic, chromium and potassium. Field analysis of water samples included temperature, pH and electrical conductivity. Water samples were also collected and analyzed for the isotopes deuterium (^{2}H) and oxygen-18 (^{18}O).

One of the main goals of the water analyses was to determine if the distribution of geochemical and isotopic species could be used to evaluate the interaction between the surface water and the shallow groundwater system beneath the Laguna Almoloya and the Lerma River. Of particular interest in this study were the vertical distributions of geochemical species directly beneath the Laguna Almoloya and the Lerma River. These geochemical profiles may provide evidence of the infiltration of surface water. This implies that a significant contrast in concentration of the selected target species must exist between the surface water source and the groundwater in the shallow sediments in order to observe a mixing process between the two sources of water. For this discussion, the data collected at Site A within Laguna Almoloya and at Site C along the Lerma River was considered in detail.

Numerical analysis

Stratigraphic information, hydraulic parameter estimations, historical hydraulic head data and geochemical information were all used to develop a hydrogeologic conceptual model of the southern part of the Lerma River Basin. This conceptual model was used to define and calibrate a numerical model, which was used to quantify groundwater and contaminant mass flux beneath the Laguna Almoloya and to predict the future evolution of the groundwater flow system.

The numerical simulations were conducted using FRAC3DVS (Therrien and Sudicky 1995), a three-dimensional, finite-element numerical model designed to simulate groundwater flow and solute transport under variably saturated conditions in massive or discretely fractured porous media. The simulation domain was defined along the instrumented cross-section shown in Fig. 4. The modeling procedure consisted of reproducing the hydrogeologic conditions along the cross-section prior to the commencement of pumping, followed by a transient analysis of the evolution of the flow system up to present day and then into the future, with the objective of estimating infiltration rates beneath Laguna Almoloya and contaminant mass flux from the Laguna to the Sistema Lerma production wells.

Results and discussion

Field investigations

Hydrostratigraphy and hydraulic conductivity

A hydrostratigraphic cross-section showing the general sedimentary structure of the near-surface materials beneath Laguna Almoloya is shown in Fig. 5. As illustrated in Fig. 4, the cross-section originates at borehole PL-126 on the western side of the Lerma River and passes through sites C, A and B before terminating at the eastern edge of the basin near PL-106 and Sistema Lerma Well 53-A. Geologic information from boreholes PL-113 and PL-109 were projected onto the cross-section and are assumed to represent the regional stratigraphy at their relative locations along the section.

The cross-section was constructed to a total depth of approximately 40 m, where detailed stratigraphic data are available, and where the most critical controls on the transient hydraulic response below the Laguna are located. At greater depths, the regional flow field in the deeper aquifer sediments is presumed to be predominantly horizontal (Lesser y Asociados 1992; DGCOH 1997) due to the influence of the Sistema Lerma wells.

The upper 15 m of the sediments are primarily silty sands with some clay and organic material (avg. $K_{\mathrm{vert}}=10^{-8}$ m/s), likely of lacustrine origin, and several discontinuous sand units. Underlying this unit are 10–20 m of organic-rich clay (avg. $K_{\mathrm{vert}}=10^{-9}$ m/s) that form a fairly continuous aquitard over the deeper sands and basalt flows. The Sistema Lerma wells are primarily completed in the basalt units along the eastern edge of the basin. Average hydraulic conductivity values for each of the main hydrostratigraphic units were derived from measurements made as part of the current study, or were drawn from previous work completed in the Lerma River Basin and the Basin of Mexico (Ortega and Farvolden 1989; Rudolph et al. 1991; Lesser y Asociados 1992; Ortega et al. 1993; DGCOH 1997; Sultan 2001). Table 1 contains a summary of the data and estimated average hydraulic conductivity values for each unit. Other physical parameters required for the subsequent groundwater flow and solute transport modeling were also drawn from previous studies conducted in the area and will be discussed in a subsequent section.

Hydraulic head measurements

Hydraulic head data collected in August 1999 during the wet season and June 2000 at the end of the dry season show only minor seasonal variations. Weak to nonexistent downward hydraulic gradients are observed in the shallow

Table 1 Final values of hydraulic conductivity and porosity, anisotropy ratios and storage coefficients applied to each of the defined hydrostratigraphic layers in the model domain based on calibration to observed field data

Stratigraphic zone	$K_{\text{Hor.}}$ (m/s)	$K_{\text{Ver.}}$ (m/s)	K_x/K_y	Porosity	Initial storage coefficient (/m)	Calibrated storage coefficient (/m)
Silty clayey sand	1.0×10^{-7}	1.0×10^{-8}	10	0.5	0.0001	0.001
Clay	1.0×10^{-8}	1.0×10^{-9}	10	0.6	0.001	0.005
Clayey sand	1.0×10^{-6}	1.0×10^{-7}	10	0.5	0.0005	0.001
Basalt	5.0×10^{-5}	1.0×10^{-5}	5	0.1	0.00005	0.00005
Sand	1.0×10^{-5}	1.0×10^{-6}	10	0.45	0.0001	0.0001

sediments beneath Laguna Almoloya at Site A, near the Lerma River at Site C and far to the west of the Laguna at Site D (Fig. 6). However, at Site B, along the eastern shore of the Laguna near the Sistema Lerma wells, there is a fairly strong downward hydraulic gradient throughout the entire shallow sediment sequence. Much stronger vertical gradients are observed deeper in the profile at Sites A and C suggesting the effect of the pumping of the production wells in the basin may still be propagating upward to the lake bottom under most of Laguna Almoloya. This will be investigated more quantitatively in the numerical modeling section below.

In general, the gentle vertical gradients in the shallow sediments at Sites A, C and D combined with the low K of the shallow sediments would suggest there is currently very little infiltration of surface water in these areas. Along the eastern shore in the vicinity of the Sistema Lerma wells, however, the effect of groundwater extraction appears to

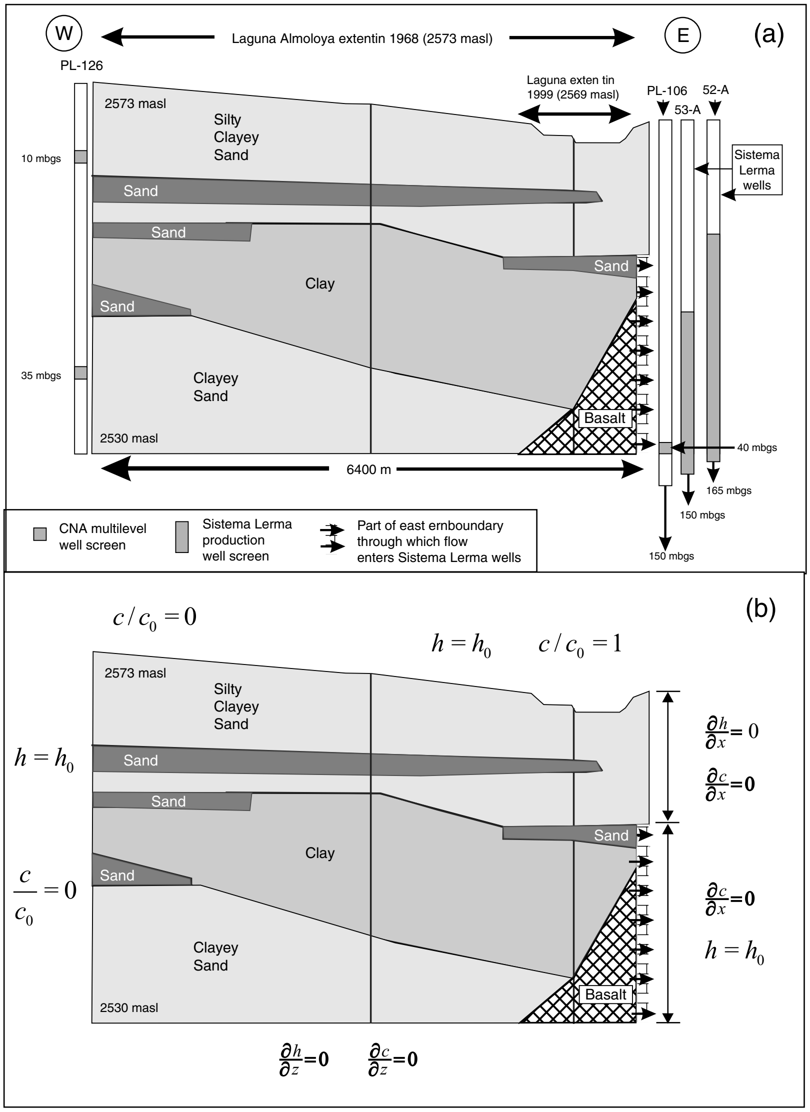

Fig. 5 Model domain showing locations (**a**) of available multilevel well data, screen locations for Sistema Lerma wells in vicinity of the cross-section, extent of Laguna Almoloya in 1968 and 1999 across the domain and the generalized hydrostratigraphic units. Boundary conditions for both the flow and transport simulations are shown in (**b**)

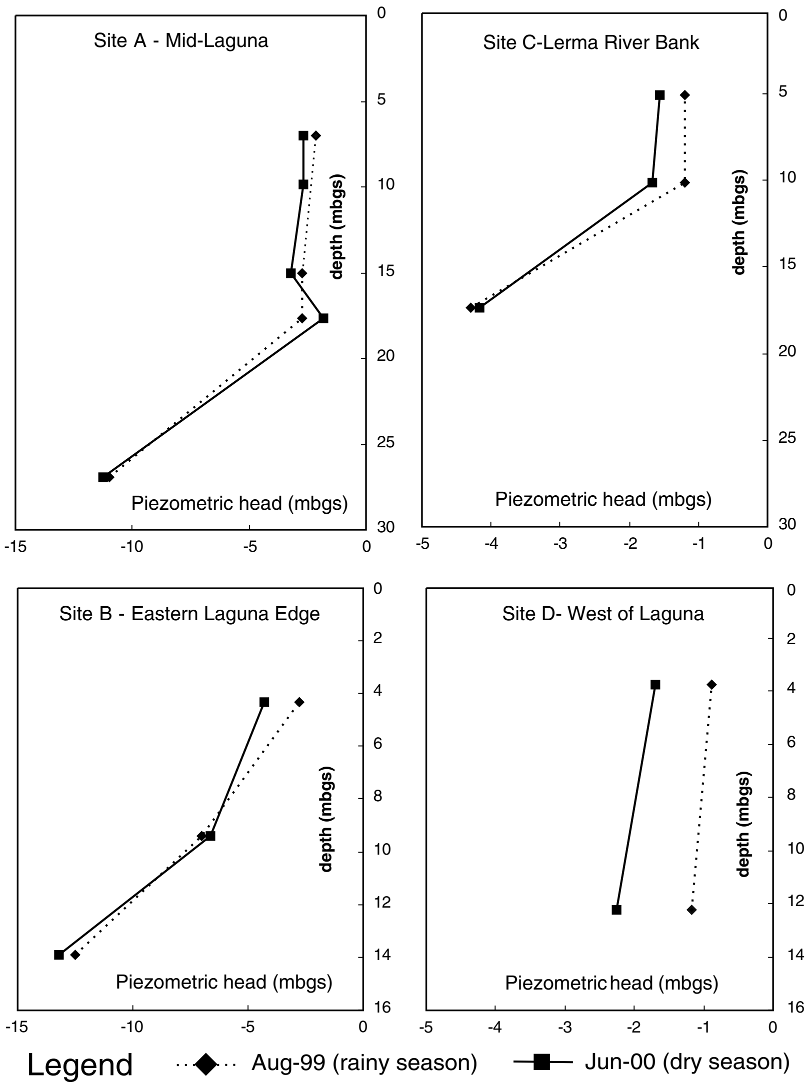

Fig. 6 Depth to piezometric level relative to ground surface (mbgs) for well clusters installed at Sites A, B, C and D measured in August 1999 and June 2000. These data illustrate variations in hydraulic head with depth at each site and the difference in the gradient with depth. The seasonal comparison shows that there are minor fluctuations in hydraulic head but little change in the gradient between the August (the rainy season) and June (the dry season). Note the different scales on each plot

have reached ground surface and the potential for infiltration of contaminated lake water exists (Site B, Fig. 6).

Vertical distribution of chloride and environmental isotopes

As groundwater tracers, chloride (Cl^-) and the environmental isotopes of oxygen-18 (^{18}O) and deuterium (^{2}H) have proven to be useful for quantifying infiltration due to their nonreactive behaviour (Appelo and Postma 1996). The distribution of these tracers throughout the flow system can indicate the degree of interaction between surface water and shallow and deep groundwater, if each water source has a distinct concentration of the tracer. This approach has proven useful in the adjacent Basin of Mexico (Rudolph et al. 1991; Ortega et al. 1999).

Figure 7 illustrates the Cl^-, ^{18}O and ^{2}H concentration profiles at Sites A and C along with the corresponding hydraulic head profiles and the hydrostratigraphic sections. For comparison purposes, the concentration of each tracer in the Laguna Almoloya is plotted as the uppermost point in the Site A profile while the Lerma River concentrations are plotted as the first data point in the Site C data. The deepest data point at Site A is based on water taken from one of the Sistema Lerma production wells located near the Laguna and is assumed to be representative of the groundwater in the deeper sediments.

All groundwater samples show relatively low Cl^- concentrations (5–20 mg L^{-1}) relative to surface water (60 mg L^{-1}). At Site A, where the shallow sediments have likely been overlain by surface water for most of their history, the Cl^- concentration in the surface water is approximately 10 times that of the shallowest well, located at a depth of 7 m (Fig. 7). Chloride concentration is lowest at 10 m and increases slightly with depth. This implies that surface water infiltration is constrained to depths of less than approximately 7 m below the Laguna bottom at Site A. A similar Cl^- profile is observed at Site C, below the Lerma River, where water has not infiltrated to depths greater than 5 m, if at all (Fig. 7).

As shown by Sultan (2001), Oxygen-18 (^{18}O) and deuterium (^{2}H) compositions of shallow groundwater obtained

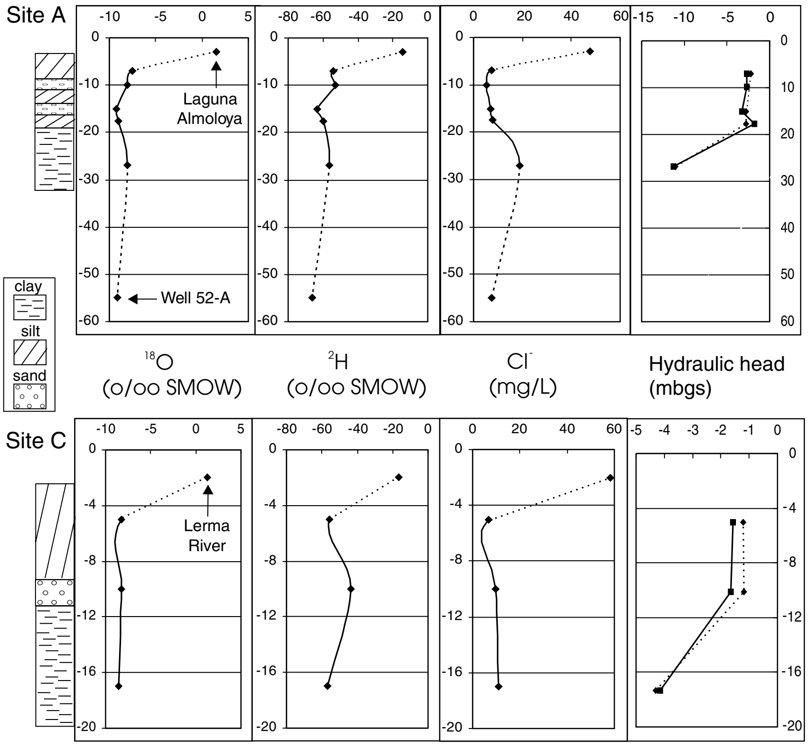

Fig. 7 Concentration vs. depth profiles for ^{18}O, ^{2}H and Cl^- at well Sites A and C. These are plotted along with variations in hydraulic head with depth and the borehole logs. Included in the plots for Site A are data from the Sistema Lerma production well 52-A (with an average screen depth of 55 mbgs) and surface water data from the Laguna Almoloya. Site C surface water data was collected from the Lerma River. Note the different depth scales between Sites A and C

from the monitoring wells and deeper groundwater collected from the Sistema Lerma wells fall in a fairly narrow range and plot close to the local meteoric water line developed for a nearby site by Cortes and Farvolden (1989). On the other hand, surface water samples collected from Laguna Almoloya and the Lerma River are significantly enriched in ^{18}O and ^{2}H, likely as a result of evaporative fractionation (Clark and Fritz 1997).

This stark difference in the isotopic signatures of the surface water and shallow groundwater provides an opportunity to examine the degree of mixing between the two waters and to estimate the amount of surface water infiltration. The vertical profiles of ^{18}O and ^{2}H for Sites A and C are illustrated in Fig. 7 and, like chloride, imply that very little mixing of the surface water and groundwater has occurred. This conclusion agrees with that drawn from the examination of the vertical gradient data presented earlier.

Numerical analysis

The modeling exercise was designed to quantitatively investigate the transient nature of the groundwater flow field and migration of potential contaminants emanating from Laguna Almoloya in the shallow sedimentary sequence at the study site. One objective was to reproduce historical flow conditions along the instrumented cross section with a focus on the evolution of vertical gradients beneath the Laguna floor. As a second objective, using the calibrated transient flow field, the infiltration of potential contaminant species from the Laguna and subsequent interception by the Sistema Lerma wells was evaluated.

Model domain

The hydrostratigraphic cross-section developed earlier (Fig. 5) was selected as the basis for the numerical analysis. Since the onset of pumping from the Sistema Lerma wells in the early 1950s, regional groundwater flow has been shown to be generally eastward in the vicinity of the study site (Lesser y Asociados 1992). For simulation purposes, the assumption is made that the cross section is oriented roughly along a flow line and that flow components perpendicular to the section are not significant.

In order to focus on the upper sedimentary sequence and to make optimal use of the available data, the maximum thickness of the domain was restricted to the upper 40 m and extended nearly 6.5 km in length. The simulated domain was discretized with 71,038 nodes and 69,653 rectangular finite elements. The average element size, chosen to minimize numerical error by meeting the Peclet criterion (Daus and Frind 1985), was 10 m in the horizontal and 1 m in the vertical direction.

Material properties

The physical parameters required for the numerical model were assumed to be uniform over each of the hydrostratigraphic units (Table 1). An anisotropy ratio (K_x/K_y) of 10 was selected to be representative of the valley fill sediments (Freeze and Cherry 1979). The permeability of the basalt unit was drawn from data presented in Ortega and Farvolden (1989) for the same formation in the Basin of Mexico along with their recommended anisotropy ratio of 5.

Storage coefficients were estimated to range between 5×10^{-5}/m and 1×10^{-3}/m with the minimum value being applied to the basalt unit and the maximum value to the

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clay aquitard (Ortega and Farvolden 1989; Rudolph and Frind 1991; Fig. 5). Porosity values were selected to range between 0.1 and 0.6 and were drawn from previous studies involving similar materials both within the Lerma Basin and elsewhere (Rudolph et al. 1991; Lesser y Asociados 1992; Ortega et al. 1993; Fidler 1998; van der Kamp 2001). Using the transport properties of chloride as an estimate for the movement of contaminants through the system, a value of 1×10^{-10} m^2/s (Parker et al. 1994) was assigned as the effective diffusion coefficient for all units. Values of longitudinal and transverse vertical dispersivity were assigned as 1 and 0.001 m respectively and were based on literature estimates (Gelhar et al. 1992).

Boundary and initial conditions for the flow simulations

The model domain and the boundary conditions specified for the flow simulations are shown in Fig. 5. Transient simulations were conducted for the time period from 1951, when the Sistema Lerma wells began pumping to 2003. Initial distributions of hydraulic head throughout the model domain in 1951 are not well documented. Data derived from the CNA multilevel wells in the mid 1960s (Fig. 2; DGCOH 1992 and Sultan 2001) suggest that the vertical gradients in the upper 50 m of the sedimentary sequence were very gentle to nonexistent in the vicinity of the study site. Although upward flow gradients may have persisted in some parts of the Basin, particularly near the lateral boundaries, the low permeability of the valley fill sediments likely minimized the influence of deep, high hydraulic head conditions within the shallow environment represented within the model domain. As a conservative estimate, hydrostatic conditions were assumed as the initial conditions for the flow simulations.

Specified, first-type conditions were specified over the majority of the domain boundaries (Fig. 5b). From 1951 to 1968, hydraulic head values observed in the vicinity of the Sistema Lerma wells were applied to the eastern boundary and allowed to propagate through the system. The head on the top of the model domain was fixed at the level of Laguna Almoloya, which then covered the entire upper boundary of the model domain (UAEM 1993; Diez 1998). The boundary conditions were then updated every 5 years from 1968 until 1993, and then for a final 6-year period from 1993 to 1999, to account for variations in pumping conditions and changes in the lateral extent of Laguna Almoloya. The upper boundary was defined as the lake level for as far as the lake extended over the area during each time period, as documented through historical records and air photos (Diez 1998). As the ground surface became more exposed with time, it was assumed that the water table remained close to it, as was observed in the shallowest monitoring point in well PL-126.

Heads at the western and eastern boundaries were set equal to the values observed in multilevel monitoring wells PL-126 and PL-106 respectively (Fig. 5) and updated based on data from these wells every 5 years during the simulations. Because the eastern boundary terminates at the Sistema Lerma wells, it acts as a groundwater divide between the basin sediments to the west and the eastern mountain range. The upper 15 m of the eastern boundary is situated above the screened intervals of the Sistema Lerma wells and consists of relatively low permeability material. The assumption was made that groundwater flow in this section of the boundary would be predominantly downward towards the basalt aquifer and as such a second-type, zero flux boundary condition was assigned. The lower 25 m of the eastern boundary represents the production aquifer and was assigned a progressively updated hydraulic head value based on data from the nearby PL-106 well.

The bottom boundary of the model domain is situated within the pumped aquifer. Considering the continuous and deep-screened intervals of the Sistema Lerma wells, the assumption is made that flow along this lower boundary would be essentially horizontal. As such, a first-type boundary condition was applied to this section of the domain based on an interpolation of historical data taken from the CNA wells PL-126, PL-113 and PL-106 (Fig. 4). As with the other boundary conditions, these values were continuously updated over time as the simulation progressed.

Results from the flow simulations

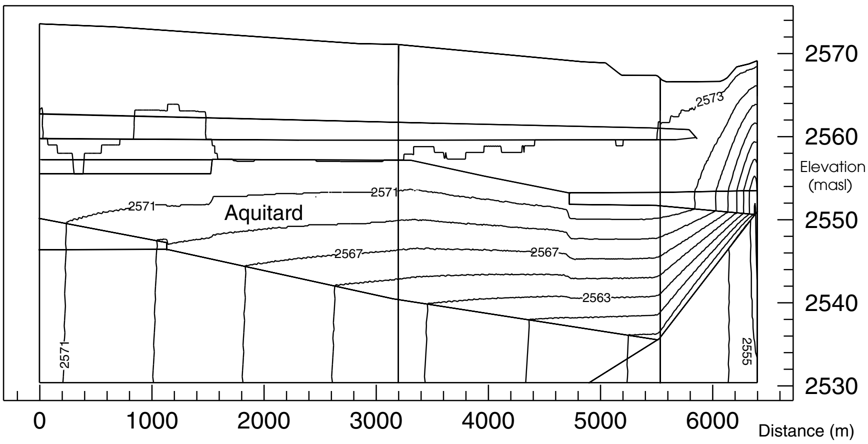
Hydraulic head values measured in the well clusters at Sites A, B and C, a total of 11 overall, were used as calibration points to insure that the model adequately reproduced flow in the near-surface environment, the most critical component of the overall flow system with respect to the current study. Calibration was achieved by modifying only the storage coefficient values and proceeded until the hydraulic head values generated by the model through the transient simulation period agreed with the 1999 field-measured values to within + or −0.5 m. The final calibrated hydraulic parameter values are presented in Table 1 and are within the range of those measured in this and previous studies in the region.

Simulated hydraulic heads for 1968 and 1999 are shown in Fig. 8, and indicate that by 1968, a small downward gradient had developed along the eastern end of the flow domain near the production wells. At this time, Laguna Almoloya covered the entire upper boundary of the flow domain and so there was a potential for infiltration along the eastern shoreline. Across the rest of the floor of the Laguna, the vertical hydraulic gradient was still low or nonexistent.

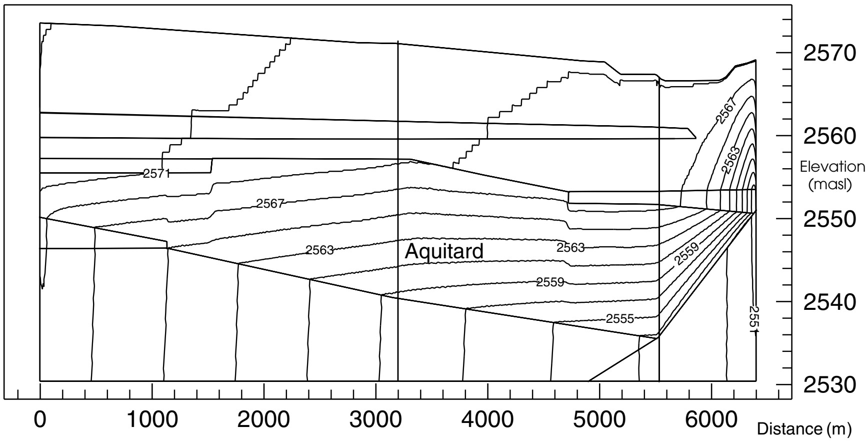
The influence of the Sistema Lerma pumping wells can be clearly seen to be migrating through the clay aquitard throughout the simulated domain. The thickness and continuity of this aquitard unit has a significant influence on the hydraulic conditions in the near surface sediments and subsequently the transient infiltration flux beneath Laguna Almoloya. As such, the lateral continuity of the aquitard is a controlling factor in the potential long-term impacts of infiltrating surface waters on the groundwater quality in the

Fig. 8 Hydraulic head elevation contours as simulated with FRAC3DVS in (**a**) 1968 and (**b**) 1999. The flow system configurations are similar in both cases, although stronger vertical and lateral gradients dominate the flow system in 1999. Note the changes in hydraulic head through the middle aquitard unit, at the eastern edge of the flow domain and along ground surface

a) 1968 (Hydraulic head contours :2555-2573 masl, every 2m)



b) 1999 (Hydraulic head contours :2551-2573 masl, every 2m)



production wells. This is particularly important along the eastern shore of the Laguna where the aquitard terminates above the basalt unit as is illustrated in Fig. 8.

By 1999, gentle downward vertical hydraulic gradients had developed beneath the entire lateral extent of the Laguna Almoloya, which by then was a significantly smaller water body (Fig. 2). Again the gradients are the strongest along the eastern shore of the Laguna. The hydraulic gradients under the remaining surface water body are still relatively low.

Simulated water fluxes were used to estimate the total amount of infiltration, which occurs below Laguna Almoloya by summing the nodal values across the portion of the top boundary that sits beneath the Laguna and extrapolating over the entire floor of the existing Laguna. By 1999, the model predicted infiltration flux is still very low, and based on the current volume of the water body, it would require approximately 450 years to drain the Laguna Almoloya through subsurface infiltration alone. Therefore, it would appear that enhanced infiltration losses, resulting from the extensive groundwater extraction by the Sistema Lerma wells, have not had a significant impact on the wetland-Laguna system.

Boundary conditions and results from the transport simulations

Using the transient flow conditions described above, the transport of solutes from the Laguna Almoloya through the groundwater system was simulated next. Although no detailed historical water quality data exist for the Laguna Almoloya until fairly recently, it is well documented that it was relatively fresh until the early 1970s, when it's aerial extent began to decrease and the domestic and industrial activities began to rapidly increase (UAEM 1993; Diez 1998). For the transport simulations, the assumption was made that the concentration of a conservative tracer representing a contaminant species in the Laguna reached levels that currently exist today at the start of the simulation period in 1973. Prior to this, the surface water is assumed to have been fresh. Although it is possible that concentrations have progressively increased slightly over time as the Laguna decreased in size, this assumption represents a worst-case scenario where contaminants have the longest possible time to infiltrate into the subsurface environment.

The transport boundary conditions were assigned by assuming that the Laguna water was the only source of solute and had a relative concentration (C/Co) equal to 1.0. The lateral extent of this boundary was initially across the entire

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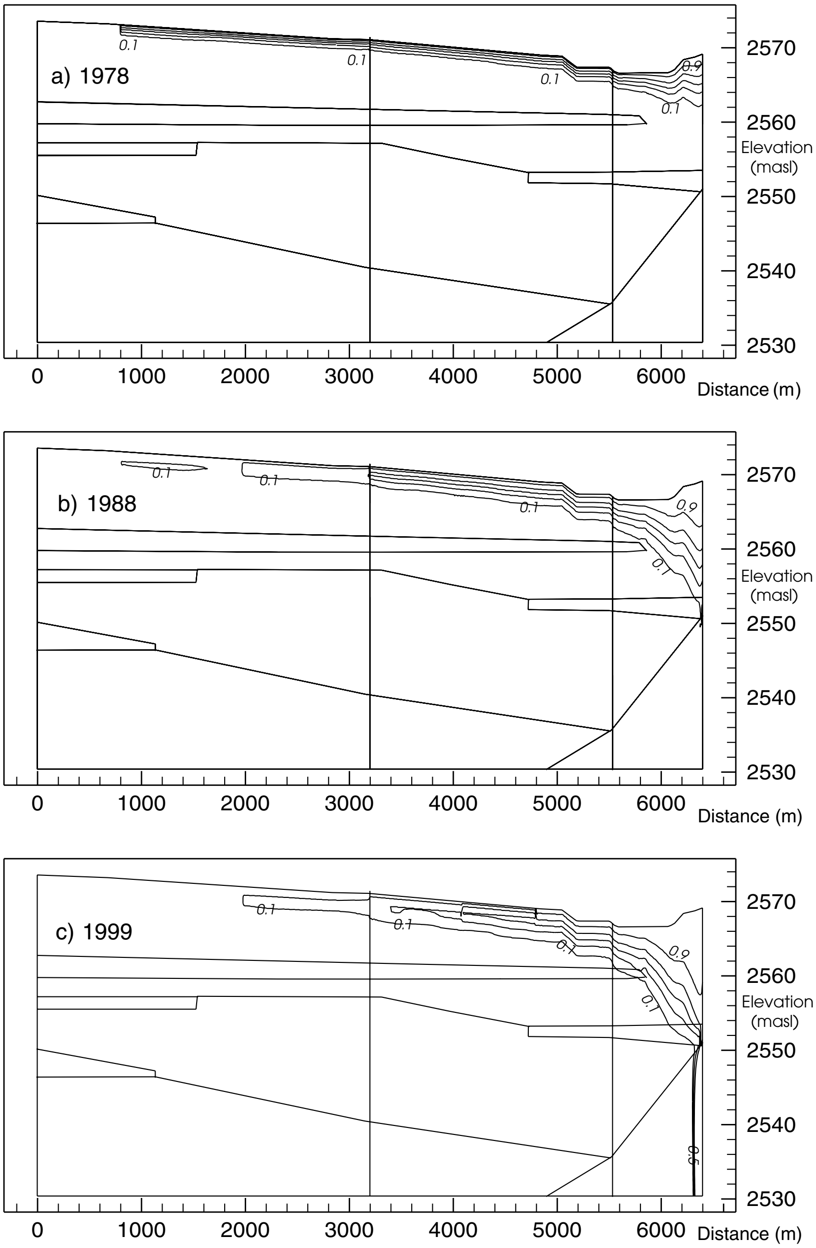

Fig. 9 Contaminant plume development below the Laguna Almoloya as simulated with FRAC3DVS in (**a**) 1978, (**b**) 1988 and (**c**) 1999. The contaminant was introduced along the top boundary in 1973 and reaches the Sistema Lerma production well screens by 1988. Concentration contours can be correlated to maximum relative concentrations C/Co = 1.0 in the Laguna

top of the domain and decreased every 5 years to correspond with the observed extent of the Laguna. The rest of the top boundary and the western boundary were assigned C/Co values equal to 0.0, while the bottom and eastern boundaries were set as zero-gradient second type boundaries. A zero-gradient second-type boundary condition, specified along the lower portion of the eastern boundary where the production well screens are located, allows mass to exit the system by advection.

The results from the transport simulations for 1978, 1988 and 1999 are presented in Fig. 9. In 1978, 5 years after the introduction of the contaminant species in the Laguna, contaminant mass has begun to migrate into the subsurface to a depth of 2–3 m under the entire extent of the Laguna, predominantly through diffusion. Along the eastern boundary where the vertical hydraulic gradients are the highest, the contaminant tracer has penetrated significantly deeper into the subsurface yet still remains well above the screened elevations of the production wells. By 1988, the surface area of the Laguna has decreased significantly and covers approximately half of the upper boundary of the domain. Through dilution and diffusion, mass that entered the system under the area originally covered by the Laguna is beginning to decrease in concentration (Fig. 9b). Where the surface water remains at the ground surface, the contaminant mass continues to migrate deeper into the subsurface but still only reaches depths of around 6 m under the majority of the Laguna floor. At the eastern boundary, however, the leading front of the infiltrating contaminant mass has reached the upper part of the basalt aquifer and is being captured by the Sistema Lerma wells. This provides a temporal constraint on the first ar-

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rivals of potential contaminants infiltrating from the Laguna Almoloya.

The simulations were then run forward to 1999 and the mass distributions are illustrated in Fig. 9c. The Laguna surface area has now reduced in size to its current position and the infiltrated mass west of the western shoreline continues to disperse whereas along the eastern edge of the domain, the concentration profile has moved deeper into the subsurface. Relative concentrations of 0.5 are intercepted by the wells at this point. The potential impact on the water quality in the wells is difficult to quantify due to the dilution effects along the entire length of the screened intervals (∼100 m). However, considering the total infiltrating water flux beneath the base of the Laguna, as estimated through the flow modeling exercise, water derived from the Laguna would only represent between 3 and 5% of the current extraction rate of a single well. This fact, along with the relatively low concentration of contaminant species considered as part of this study would again support the conclusion that the impact of the groundwater quality from infiltrating Laguna water is minimal. The simulation results do, however, suggest there is a significant possibility that nonretarded contaminant species originating in Laguna Almoloya are currently being captured by some of the Sistema Lerma production wells. More detailed assessment of the nature of the groundwater contaminants in the Laguna and their mobility in the subsurface appears warranted particularly for contaminants that are toxic at very low concentrations and pathogens.

It is also of interest to compare the vertical distribution of a conservative tracer such as chloride measured beneath the Laguna to the simulated distribution from the modeling results. Data collected at Site A, in the center of the Laguna (Fig. 4), was compared to the vertical solute profile generated by the model in 1999 at this same location. The comparison is illustrated in Fig. 10. Although the simulations assumed that the initial concentrations for the modeled tracer everywhere in the domain were zero as opposed to the background values of between 5 and 10 mg L^{-1} for chloride, the two profiles suggest very similar depths of penetration and overall shape providing an additional degree of confidence as to the representativeness of the simulation results.

Conclusions

The documented decrease in lateral extent of the large lake and wetland system within the Toluca Basin, Mexico, can be temporally linked to the development of extensive groundwater resource development in the immediate vicinity. The hydrologic mechanisms that have resulted in these significant impacts may include decreases in discharge from surface and groundwater pathways, enhanced surface water drainage and/or increased infiltration losses as a result of depressurization of the underlying sediments. The current study focused on the significance of enhanced infiltration related to extensive groundwater extraction in the Toluca Basin.

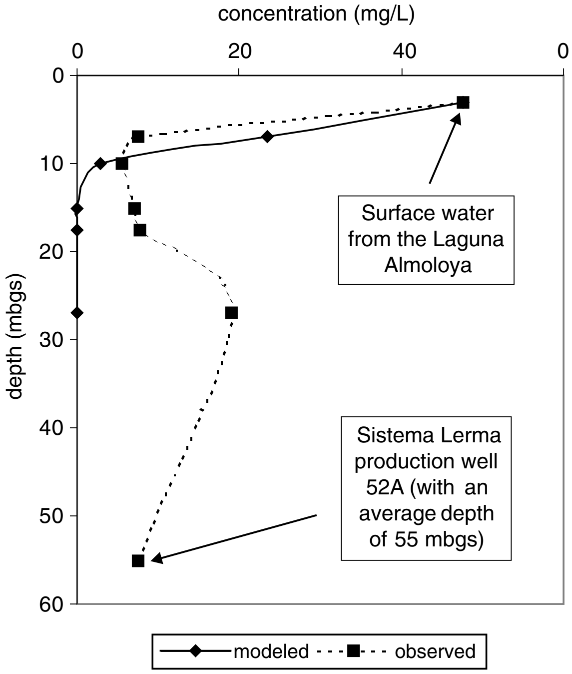

Fig. 10 Contamination concentration with depth at Site A. The simulated results for a nonreactive tracer are compared to the actual measured concentrations of chloride in the five monitoring wells at Site A, in the Laguna Almoloya and in Sistema Lerma production well 52-A. Note that the simulations assume a zero initial concentration for the modeled tracer

Historical records of hydraulic head obtained from a network of deep multilevel piezometers located near the wetland system indicate a progressive increase in downward vertical hydraulic gradient over time. The major changes in vertical gradient have occurred since the large Sistema Lerma well field was installed along the eastern edge of the Toluca Basin in 1951. The piezometric data collected from monitoring well clusters located in the vicinity of the last remaining water body Laguna Almoloya, indicate that this increase in vertical gradient has not yet reached ground surface under the majority of the wetland area. Geochemical and isotopic data collected from the shallow monitoring well clusters suggest that there has been little infiltration of surface water under the Laguna. The zone of surface water-groundwater mixing is constrained to the upper 5–10 m of the subsurface sediments at the locations investigated. The combined data suggest that the extensive groundwater extraction from the Sistema Lerma wells has not significantly enhanced infiltration beneath the lagoon region in southern Toluca Basin. It is unlikely that this has been a significant factor in the progressive reduction in the size of the wetlands and lakes.

Although the geochemical and isotopic data collected in the near surface environment suggest very little movement of contaminants from the floor of the Laguna to the groundwater system, contaminant transport simulations indicated that a significant component of downward groundwater flow is likely occurring along the eastern edge of the basin, near the Sistema Lerma well field. The results suggest that there is a strong possibility that the production wells have

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been intercepting infiltrated Laguna Almoloya water for at least the last decade. The level of impact this infiltrating water currently has on the water quality is difficult to assess due to the complex fate and transport behaviour of many of the contaminant species. The simulations suggest, however, that only a small fraction of the groundwater currently extracted by the Sistema Lerma wells located near Laguna Almoloya, originates in the Laguna.

One of the most significant factors controlling the influence of groundwater pumping on the wetland system, appears to be the existence and lateral continuity of an organic clay aquitard in the shallow subsurface. Both the field data and modeling results illustrate the role of the aquitard in dampening the rate of depressurization beneath Laguna Almoloya. Where the aquitard thins out near the eastern edge of the basin, vertical groundwater flow appears to increase significantly. The long-term impacts on water quality in the Sistema Lerma production wells may depend to a large extent on the continuity of this aquitard unit. More detailed investigation into the lateral distribution of the aquitard in the vicinity of the production wells and elsewhere beneath the Laguna Almoloya, is a topic for continued research with respect to the dynamics of groundwater-surface water interaction in this region.

The gradual disappearance of the lake and wetland system in the southern Lerma River Basin does not appear to be related to enhanced infiltration due to the extensive groundwater extraction in the immediate vicinity as had been previously suspected. The influence of modifications to surface drainage and changes to the recharge from groundwater and surface water sources as a result of the groundwater extraction are now under additional investigation. In addition, impacts on the groundwater quality in the Sistema Lerma production wells from infiltrating surface water in Laguma Almoloya appear to be minimal, but warrant additional consideration with respect to a wider spectrum of potential contaminant species.

Assessment of these types of hydrologic impacts on regional wetland systems requires a combined approach of field investigation and numerical analysis in order to develop a sufficient understanding of the complex groundwater-surface water interactions. The approach developed for the current study site may prove useful at other similar areas where groundwater extraction is anticipated to be influencing regional wetland systems.

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