Chapter 33
Influence of Interactions of Surface Waters: Groundwaters on the Chemistry of Surface Waters in the River Andarax Catchment (Almería, SE Spain)

F. Sánchez-Martos, J. Gisbert Gallego, L. Molina Sánchez, and A. Pulido-Bosch

Abstract Interactions between surface water and groundwater (SW-GW) in the Andarax catchment are complex and encourage a diversity of surface waters in the three longest watercourses. The headwaters of the river Andarax flow continuously, but it is temporal in its middle reaches and ephemeral in its lower reaches; these three reaches demonstrate the effect of GW-SW dependence. Water quality is also affected by increases in nitrate and salinity in different stretches. The middle reach of the river Nacimiento carries a permanent flow due to a diffuse discharge of groundwater. In the Tabernas rambla (gulley), there is a perennial saline water flow associated with a discharge of saline groundwater, but this is not continuous over the length of the watercourse. Understanding the diversity of situations linked to GW-SW interactions is essential in this semi-arid area if its water resources are to be managed properly; therefore, these interactions need to be borne in mind when considering the water quality indicators of the surface waters.

Keywords Surface and groundwater • Andarax catchment • Water quality • SE Spain

33.1 Introduction

Groundwater-surface water (GW-SW) interactions in semi-arid areas are complex and poorly understood. Understanding their interactions helps understand the hydrological behaviour of Mediterranean rivers, as the presence of surface water in these watercourses is often related to GW-SW interactions and the typology of geological substratum. As a result, understanding and characterizing the

F. Sánchez-Martos (✉) • J. Gisbert Gallego • L. Molina Sánchez • A. Pulido-Bosch
Department of Hydrogeology, University of Almería, Campus Universitario, Almería, Spain
e-mail: fmartos@ual.es

H. Farfán González et al. (eds.), *Management of Water Resources in Protected Areas*, Environmental Earth Sciences, DOI 10.1007/978-3-642-16330-2_33,

hydrological peculiarities of each watercourse is a necessity if water resources are to be managed sustainably. Historically, these temporal water bodies have not been fully integrated into the management of the catchment. In fact, they are insufficiently dealt with in regulations such as the EU Water Framework Directive. In semi-arid regions, the impact of this can be significant and may create numerous difficulties for water resources management Sophocleous (2002). Complex aquifer geology has a profound influence on river-aquifer interactions and on the water balance of the catchment (Fleckenstein et al. 2006). Even flooding can affect the GW-SW exchanges (Doppler et al. 2007). The marked effect of the landscape on flow in the river corridors and on the mobilization of nitrates must also be considered in all these processes (Vidon and Hill 2004).

The Andarax catchment (2,265 km^2) includes parts of two singular Protected Natural Spaces: the upper slopes of the Sierra Nevada are protected as a National Park and the Tabernas Desert is a so-called Natural Enclave. In addition, the catchment includes three Sites of Community Interest that form part of the European Ecological Network "Natura 2000": the "Ramblas of Gérgal and Tabernas" and "Sur de Sierra Alhamilla" and the "Sierras of Gádor and Enix". The catchment exhibits wide climatic variability that determines its plant cover, ecosystems, water availability and the various traditional land uses, and means that the hydrodynamics of the main watercourses are highly variable from a hydrological point of view.

The present study addresses GW-SW interactions in semi-arid areas from a hydrogeological point of view. It focuses on the three longest watercourses of the Andarax catchment, each of a different type, showing a wide variety of processes where groundwater plays a significant role.

33.2 Methods

33.2.1 Study Area

A wide diversity of rocks outcrop in the Andarax catchment. In the Sierra Nevada and Sierra de los Filabres, the main outcrops are basically micaschists and quartzites, while the slopes of the Sierra de Gádor are mainly limestone-dolomites. Marls with sandy intercalations and some gypsum beds are widely distributed along the valley of the Rambla de Tabernas, while along the valleys of the Bajo (Lower) Andarax and River Nacimiento are detritic deposits. The two most important aquifers of the Andarax valley are the Sierra Gádor Carbonate Aquifer and the Detritic Aquifer of the Middle and Lower Andarax. The carbonate aquifer is composed of limestones and dolomites that outcrop along the edge of the Sierra de Gádor. The detritic aquifer extends along the central portion of the valley and consists of alluvial and delta deposits, together with deltaic sandy-silty conglomerates (Sánchez Martos 1997). The aquifer formations of the river Nacimiento are detritic. Finally, the strata along the Rambla de Tabernas are mostly

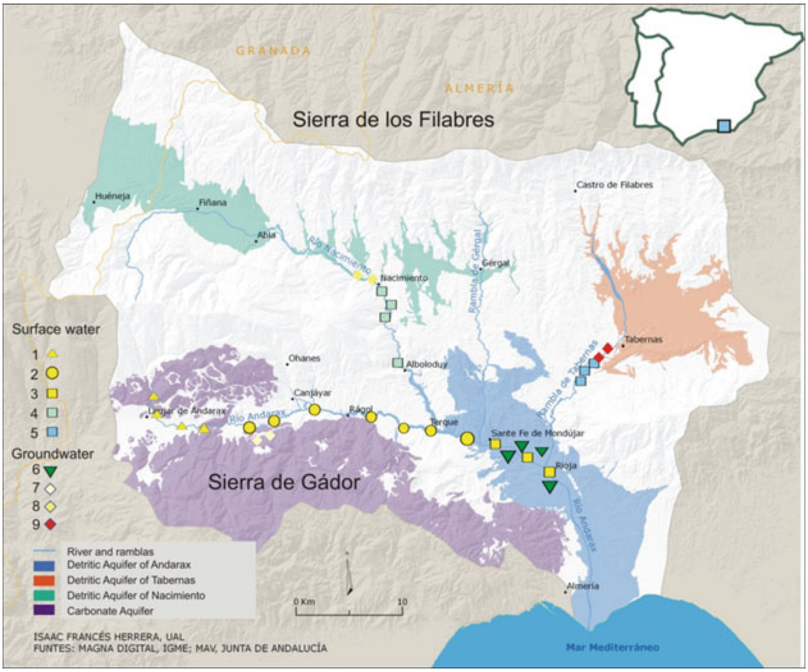

Fig. 33.1 Scheme of the Andarax catchment showing sampling points along the three watercourses studied. Surface waters: River Andarax (1: headwaters, 2: middle reach, 3: lower reach), River Nacimiento (4), Tabernas Rambla (5). Groundwaters: River Andarax Valley (6: Detritic Aquifer, 7: Carbonate Aquifer), river Nacimiento Valley (8), valley of the Tabernas Rambla (9)

impermeable, and the aquifer deposits correspond to alluvial sands and conglomerates. These alluvia cover a large surface area but their aquifer potential is restricted, given their limited depth.

33.2.2 Data

The monitoring network devised centers on the stretches of the watercourse carrying temporal surface flow, and the groundwaters in their vicinity (Fig. 33.1). Fourteen points were sampled along a 35 km stretch in the Andarax valley, with four sampling surveys made over the course of 1 year. The corresponding groundwater data considered are from the Sierra de Gádor Carbonate Aquifer and the Detritic Aquifer. Seven surface water and three groundwater points were selected in the Nacimiento valley, while in the Rambla de Tabernas 11 surface water and 6 groundwater points were sampled, with samples taken at different times. The physico-chemical parameters analyzed were: electrical conductivity, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, Na^+, Mg^{2+} and Ca^{2+}.

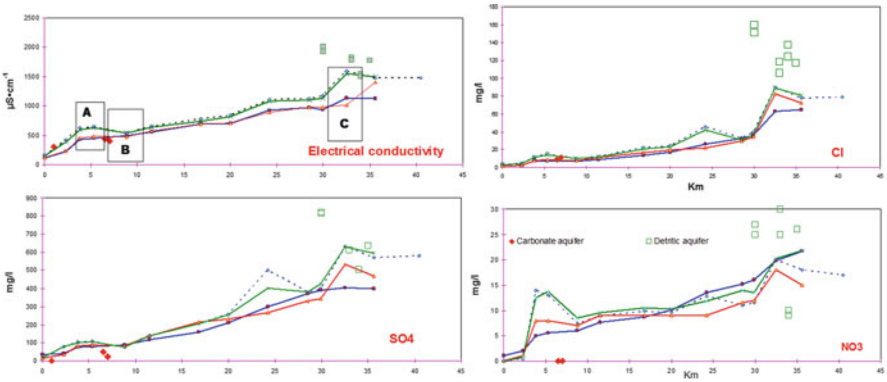

Fig. 33.2 Longitudinal evolution of electrical conductivity ($\mu S{\cdot}cm^{-1}$), Cl^-, SO_4^{2-} and NO_3^- ($mg{\cdot}L^{-1}$) in the surface and groundwaters in the Andarax valley

33.3 Results and Discussion

33.3.1 River Andarax

Groundwater in the Carbonate Aquifer has low salinity (305–441 $\mu S{\cdot}cm^{-1}$) and a calcium bicarbonate-sulphate facies. Waters in the Detritic Aquifer are more saline (1,510–2,010 $\mu S{\cdot}cm^{-1}$) and include a wide range of facies. The surface water undergoes saline enrichment along their watercourses, causing an evolution from a bicarbonate to a sulphate facies (Fig. 33.2). Rather than being gradual, this evolution includes several significant jumps in both directions.

In the headwaters (area A in Fig. 33.2), salinity is low, although there are local rapid increases in conductivity (650 $\mu S{\cdot}cm^{-1}$), sulphates (109 $mg{\cdot}L^{-1}$) and nitrates$^-$ (14 $mg{\cdot}L^{-1}$). The increase in nitrate content is marked (mean 4.5 $mg{\cdot}L^{-1}$), given the low salinity. Nitrate content of the surface waters is directly correlated with salinity ($r^2 = 0.78$) (Fig. 33.3). Nevertheless, three sampling points in the headwaters lie above the line of best fit in Fig. 33.3, indicating a local influence that pushes up NO_3^-. These three points lie in the depression of Laujar de Andarax, where traditional agricultural activities are quite intense. The peak values may relate to leaching of agricultural NO_3^-, which infiltrates the aquifer and later appears in the flow of the river Andarax (Duff and Triska 2000; Lamontagne et al. 2005).

In the area denoted B, electrical conductivity is lower than at nearby sampling points (Fig. 33.2). In this stretch, the river flows through the carbonate strata of the Sierra de Gádor. Groundwater from the carbonate aquifer flows towards the river, causing a fall in salinity, though other physico-chemical parameters are maintained throughout the year-long sampling period Sánchez-Martos et al. (2004).

Conductivity in area C rises markedly over a wide range. Sulphate concentrations here are the highest recorded in the study (Fig. 33.2). The evolution of surface flow

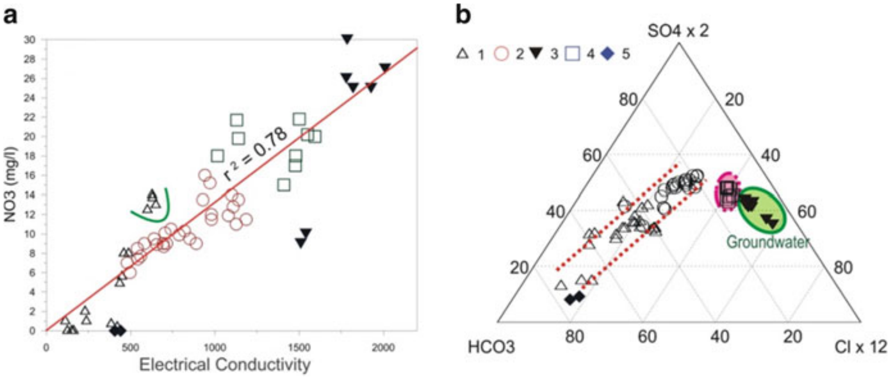

Fig. 33.3 (**a**) Nitrate content vs electrical conductivity in the river Andarax. (**b**) Triangle diagram for HCO_3^- – SO_4^{2-} × 2 – Cl^- × 12, distinguishing the surface water groups mentioned in the text (1: headwaters, 2: middle reach, 3: lower reach) and the groundwater groups (4: detritic aquifer, 5 carbonate aquifer)

in the headwaters and in the middle reach is similar (Fig. 33.3b). Sampling points are well aligned in the graph: as the percentage HCO_3^- falls, there is a corresponding increase in the percentages of Cl^- and SO_4^{2-} . In the final reach, their evolution is distinct, whereby the percentage of HCO_3^- falls and there is a gradual increase in Cl^-, while the proportion of SO_4^{2-} remains constant. The groundwater of the detritic aquifer contains higher Cl^- as a consequence of the marly deposits forming the base of the aquifer in this zone. These marly strata have been tectonically lifted, and they encourage the flow of deeper, more saline groundwater towards the surface of the aquifer. This influence is more pronounced during dry-weather periods when river flow declines and becomes discontinuous and ephemeral.

33.3.2 River Nacimiento

Groundwater was sampled from two galleries just upstream of the reach carrying perennial flow in the river. The groundwater facies is magnesium sulphate and conductivity, 1,200 $\mu S \cdot cm^{-1}$. The river Nacimiento flows along its entire length only after intense rainfall, though there is a small perennial flow in its middle reaches, from which samples could be taken and analysed. This water had a mixed sulphate facies and a salinity of between 1,200 and 2,100 $\mu S \cdot cm^{-1}$.

The perennial surface flow is fed from groundwater from the detritic aquifer in the Nacimiento valley. This flow is favoured by the presence of metamorphic rocks at the western extreme of the Sierra Nevada that form the impermeable base of the aquifer. This diffuse discharge along the riverbed causes higher ion content in the surface water than in the groundwaters sampled upstream. This diffuse inflow into the river represents a homogenization of the groundwaters, given that Cl^- and SO_4^{2-} are

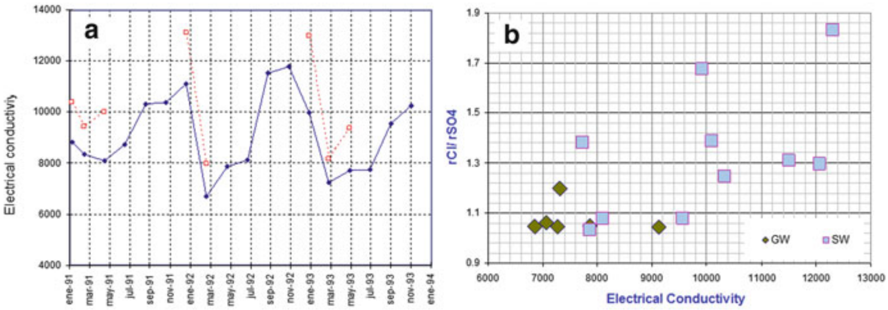

Fig. 33.4 (**a**) Evolution over time of the two surface water monitoring points in the Tabernas rambla. (**b**) Relationship rCl^-/rSO_4^{2-} vs electrical conductivity ($\mu S \cdot cm^{-1}$) for water in the Tabernas rambla

correlated ($r^2 = 0.81$) for the surface waters. The points yielding the highest nitrate concentration (10 $mg \cdot L^{-1}$) are downstream, close to Alboloduy, and probably arise as a consequence of the traditional farming activities along the river corridor.

33.3.3 Rambla de Tabernas

The groundwater comes from small, continuous surgences that drain the sandiest outcrops within the marly deposits along the margins of the watercourses. The water has a sodium chloride facies and salinity is between 6,800 and 9,100 $\mu S \cdot cm^{-1}$; thus the groundwater is more homogenous and slightly less saline than the surface waters. The surface waters have a sodium chloride facies and salinity of 7,730–13,000 $\mu S \cdot cm^{-1}$, with elevated Cl^-, SO_4^{2-} and Na^+ content. Salinity takes on a seasonal cycle, increasing during the summer-autumn and falling sharply in winter and spring (Fig. 33.4a). Despite these variations, electrical conductivity and rCl^-/SO_4^{2-} ratio are both higher than in the groundwater (Fig. 33.4b). This evolution indicates a process of cyclical saline enrichment in the watercourse over the year. Evaporation is greatest during the dry weather, therefore, increasing salinity and depositing salts that are subsequently washed downstream during the wetter seasons.

Groundwater discharge has occurred under various hydrogeological situations over time, as evidenced by the Quaternary travertine deposits that are associated with a regional fracture series (Sanz de Galdeano et al. 2008), and where there are present-day seepages of highly saline water and saline deposits.

33.4 Conclusions

The GW-SW interactions in semi-arid areas are complex and varied and give rise to diverse surface waters. The three longest watercourses of the Andarax catchment clearly exhibit the varied typology that is typical of semi-arid areas. The headwaters of the river Andarax flow continuously, while the river is temporal in its middle reach and ephemeral in the lower part. Meanwhile, the river Nacimiento is a discontinuous watercourse that has a small permanent flow in its middle reach but only flows along its whole length following intense rain. The rambla de Tabernas carries a series of small surface flows of saline water that derive from highly saline groundwater that are discontinuous in space but continuous through time.

Thus, it is demonstrated that a detailed understanding of the dependence of surface water on groundwater is essential for proper management of the associated ecosystems. The health of riverine ecosystems is heavily dependent on groundwater. This influence can work in either direction, either 'improving' or 'worsening' salinity of the surface waters, and the anthropic effects can be significant.

Lastly, the importance of understanding all the processes associated with the GW-SW interactions cannot be overemphasized in terms of the management of protected spaces in these semi-arid areas, given that the emergence of different water types favours biodiversity and needs to be considered when water quality indicators are being interpreted.

Acknowledgments This work was undertaken within the framework of project PO6-RNM-01696, financed by the Junta of Andalucía.

References

Doppler T, Franssen H, Kaiser H-P, Kuhlman U, Stauffer F (2007) Field evidence of a dynamic leakage coefficient for modelling river-aquifer interactions. J Hydrol 347:177–187

Duff JF, Triska FJ (2000) Nitrogen biogeochemistry and surface-subsurface exchange in streams. In: Jones JB, Mulholland PJ (eds) Streams and ground water. Academic, San Diego, pp 197–220

Fleckenstein JH, Niswonger RG, Fogg GE (2006) River-aquifer interactions, geologic heterogeneity and low flow management. Groundwater 44(6):837–852

Lamontagne S, Leaney FW, Herczeg AW (2005) Groundwater–surface water interactions in a large semi-arid floodplain: implications for salinity management. Hydrol Process 19:3063–3080

Sánchez Martos F (1997) Estudio hidrogeoquímico del Bajo Andarax (Almería). Tesis doctoral, Universidad de Granada

Sánchez-Martos F, Pulido-Bosch A, Vallejos Izquierdo A, Gisbert Gallego J, Fernández Cortés A (2004) Consideraciones sobre la evolución hidrogeoquímica de las aguas superficiales en el río Andarax (Almería). Geotemas 6(4):185–188

Sanz de Galdeano C, Galindo-Zaldívar J, Morales S, López-Chicano M, Azañón JM, Martín Rosales W (2008) Travertinos ligados a fallas: ejemplos del desierto de Tabernas (Almeria, Cordillera Bética). Geogaceta 45:31–34

Sophocleous MA (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10:52–67

Vidon PGF, Hill AR (2004) Landscape controls on nitrate removal in stream riparian zones. Water Resour Res 40 W03201 doi: 10.1029/2003WR002473