Modeling stream-aquifer interactions in a shallow aquifer, Choele Choel Island, Patagonia, Argentina

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Abstract A groundwater/surface-water interaction model was developed for the shallow alluvial aquifer of the Choele Choel Island in Patagonia, Argentina. In this semiarid climate, agriculture is sustained by an irrigation/drainage system. During the irrigation season, seepage losses through unlined distribution canals in irrigated fields contribute to elevated groundwater levels, jeopardizing fruit productivity in some areas. Moreover, high stream stages during the irrigation season interfere with groundwater drainage. The model utilized MODFLOW and its stream package, and was successfully calibrated for a historical irrigation season. Modeling results indicate that drainage through streams is significantly higher than drainage through artificial drains. The stream/aquifer relationship proved very responsive to water table rises caused by irrigation. This response manifested as changes in the gaining/losing character of stream reaches. A synthetic run aimed at isolating the effect of streamflow changes on groundwater levels showed that the effect of higher streamflows dissipates toward the interior of the island, disappearing completely at the island center. Even though some results were qualitative, the model helped to provide a better understanding of the coupled system to elucidate some of the causes of a rising water table on the island.

Résumé Un modèle pour étudier les interactions entre les eaux souterraine et les eaux de surfaces a été développé pour l'aquifère de l'île Choele Choel en Patagonie, Argentine. Dans ce climat semi-aride, l'agriculture est soutenue grâce à l'irrigation et aux systèmes de drainage. Durant la saison de l'irrigation, les pertes par infiltration le long des canaux de distribution dans les champs irrigués, contribuent à l'élévation des niveaux de l'eau souterraine, compromettant la productivité des fruits dans certaines zones. D'ailleurs, les niveaux élevés des rivières durant les saisons de l'irrigation, interfèrent avec le drainage des eaux souterraines. Le modèle utilise MODFLOW ainsi que son module Stream (Rivière), et a été calibré avec succès sur une saison d'irrigation historique. Les réwsultats de la modélisation indiquent que le drainage à travers les rivières est significativement plus important que le drainage à travers les drains artificiels. Les relations entre les rivières et les aquifères sont influencées par les remontées des eaux souterraines dues à l'irrigation. Cette relation d'influence manifeste des gains ou des pertes dans les lits des rivières. Une simulation visant à isolé l'effet des variations du niveau de la rivière, montrent que l'effet des niveaux élevés de la rivière se dissipe vers l'intérieur de l'île, disparaissant complètement au centre de cette dernière. Même si certains résultats sont qualitatifs, le modèle a aidé à mieux comprendre les interactions et a expliquer la remontée des nappes dans l'île.

Resumen Se desarrolló un modelo de la interacción río/acuífero en el acuífero aluvial de la Isla de Choele Choel, Patagonia, Argentina. Dadas las condiciones semiáridas, la agricultura prospera bajo riego. Durante la temporada de riego, las pérdidas en los canales de riego y en las áreas regadas incrementan los niveles freáticos, afectando la productividad de plantas frutales. Además, los niveles elevados de los ríos durante la temporada de riego interfieren con el drenaje subterráneo. MODFLOW con su Stream Package fue exitosamente calibrado para un período histórico. Los resultados del modelo mostraron que el drenaje a través de los ríos es mayor que a través de los drenes artificiales. La relación río/acuífero respondió activamente a los incrementos de niveles subterráneos producidos por el riego, con tramos de río que aportaban o recibían agua del acuífero alternativamente. Una simulación sintética realizada a fin de investigar el efecto de mayores caudales sobre los niveles subterráneos mostró que el efecto irradia hacia el interior de la isla hasta desaparecer por completo en el centro. Aún cuando algunos resultados son de carácter cualitativo, el modelo fue de ayuda para entender mejor el sistema río/acuífero, y así identificar algunas de las causas del incremento de niveles freáticos.

Keywords Groundwater/surface-water relations · Numerical modeling · Argentina

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Received: 28 May 2005 / Accepted: 14 June 2005

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DOI 10.1007/s10040-005-0472-3

Introduction

River-aquifer interactions are at the very core of the hydrological cycle. However, as stated by Younger (1995), process descriptions and engineering analyses of river-aquifer interactions have been traditionally impaired by two obstacles: one cultural, one practical. The cultural obstacle relates to a sub-discipline boundary between hydrogeology and surface hydrology, with researchers in each discipline feeling slightly uneasy at approaching the field of the other. Younger (1995) recognized that this trend has been less marked in the North American school, where the U.S. Geological Survey conducts national scientific studies in both sub-disciplines.

The practical obstacle to river-aquifer investigations arises from the disparity in response times of surface waters and groundwaters to dynamic variations in the systems. Whereas response times to variations in surface waters may be on the order of hours or days, groundwater response times may be on the order of weeks, or months or longer time periods. Due to this difference in time response, numerical modeling of stream-aquifer systems has typically been approached either by using a single model or a coupled model. In the former case, a groundwater model solves the surface component in a simplified manner. MODFLOW (McDonald and Harbaugh 1988), a finite-difference groundwater flow model, has been used in many engineering applications whenever the single model approach is sought (see for example Sophocleous and Perkins 1993). In the second case, a ground-water flow model is coupled internally or externally to a surface-water flow model. The physically based groundwater flow equation and the unsteady open-channel flow equations are solved either as a single time step (Pinder and Sauer 1971) or as multiple time steps (Swain and Wexler 1996; Nobi and Das Gupta 1997; Vionnet and Rodríguez 1998).

It is then generally accepted that the simultaneous solution of the groundwater flow equation and the unsteady open-channel flow equations overcomes many of the drawbacks attributed to the single model approach. However, this approach may demand a computational effort that cannot be fully justified in cases where streamflows show smooth variations or when the objective of the study is just to determine the average system behavior over a period of time that largely exceeds the response time of the surface component. In those and other situations, MODFLOW allows simulation of river-aquifer interactions by means of alternative add-on packages. The original RIVER package considered constant river heads and no variation in river flows (McDonald and Harbaugh 1988). This package was later surpassed by the STREAM package (Prudic 1989), which allowed calculation of river stages by introducing a mass balance computation for river-aquifer flows, among other major improvements. In the nineties, Swain and Wexler (1996) coupled the model BRANCH to MODFLOW to create MODBRANCH. Other recent MODFLOW modifications include adaptations of the STREAM package input parameters to be used under the new MODFLOW 2000 structure (Harbaugh et al. 2000).

MODFLOW continues to be a commonly used tool for approaching diverse surface water/groundwater flow problems. As such, its applications are quite vast and only a handful of them are reviewed here. Sophocleous and Perkins (1993) implemented MODFLOW with the stream/aquifer capabilities of the STREAM package, combined with a parameter estimation package and sensitivity analysis. The aim of their study was to develop a predictive tool for evaluating various management alternatives for restoring streamflows in two streams in Kansas, USA. The STREAM package was also implemented by Rodríguez and Maddock (1993) on the Upper San Pedro River, Arizona, USA, in order to get a better understanding of the stream-aquifer relationship along a riparian corridor that was being threatened by excessive groundwater pumping. In a later paper, Sophocleous et al. (1998) compared MODFLOW results with the stream depletion model of Glover and Balmer (1954). They also investigated the impact of the model grid size on estimating stream leakage. Recently, Woessner (2000) presented an application of MODFLOW combined with MODPATH and MT3D96 where numerical results were used to analyze flow patterns for channel-bed exchange processes at an experimental scale.

Irrigated stream-aquifer systems commonly suffer pumping-induced stream depletion due to extensive groundwater withdrawals. In these cases, conflicts between surface water and groundwater user groups occur frequently. The abundant literature on this topic includes the pioneer works of Theis (1941), Glover and Balmer (1954), and Hantush (1965) as well as more recent developments in analytical formulations (Fox et al. 2002) as well as numerical applications (Chen and Shu 2002). The conflict examined in the present work results from excess groundwater rather than a surface-water depletion problem, as explained below.

Relatively little published work examines stream-aquifer interactions around an island where agricultural activities prosper under irrigation, and the water is extracted from surface water sources. Such a condition exists on the Choele Choel Island in the semiarid Argentinean Patagonia, bordered by two branches of the Rio Negro (Black River) (Fig. 1). In spite of the great improvements in fruit plant productivity since the inception of irrigation, some portions of the island are still affected by poorly drained soils and a high water table. During the irrigation season, which extends from late August to early April, seepage losses through unlined distribution canals and in irrigated fields cause water-table mounding and/or soil water logging at some locations, jeopardizing fruit plant productivity and creating soil salinization problems due to groundwater evaporation. Moreover, high stream levels caused by hydroelectric power generation at upstream dams during the peak of the irrigation season interfere with free groundwater drainage. Downstream farmers maintain that hydroelectric power companies are responsible for the problem with high stream stages, while power companies claim that inefficient irrigation practices are the actual cause of the problem.

In light of the aforementioned conflict, the objective of this report is to investigate numerically the driving

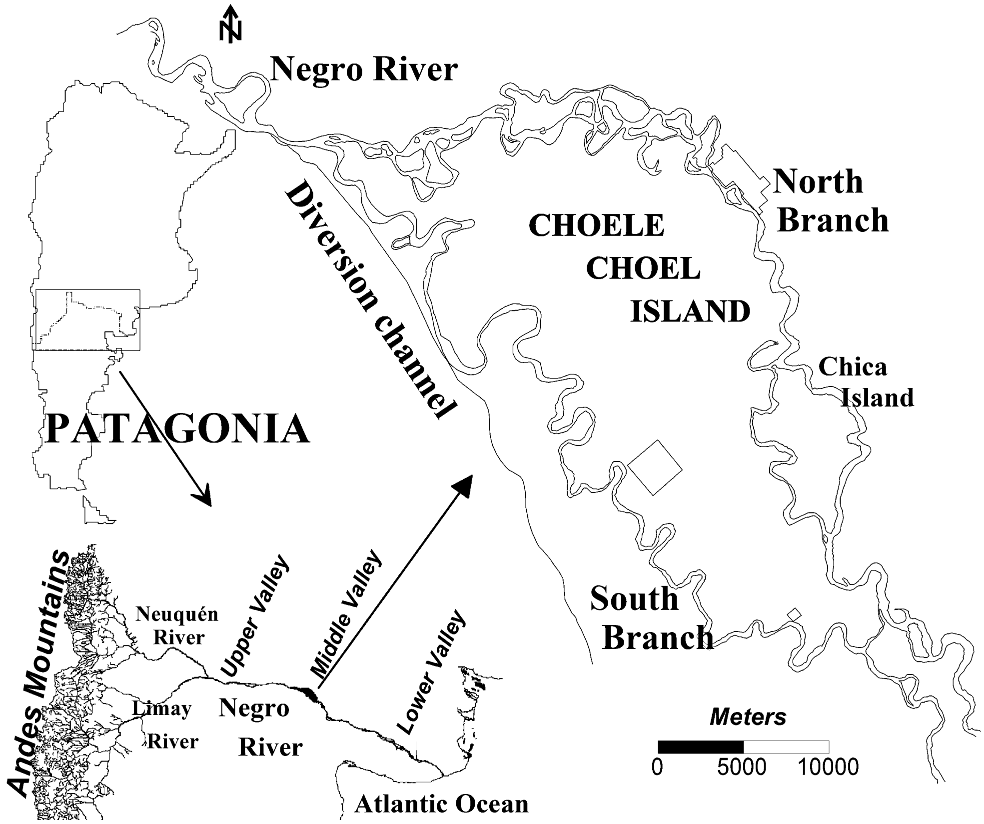


Fig. 1 Location of study area

mechanisms responsible for water-table mounding on the island. Groundwater flow and water exchange processes between the floodplain aquifer and the surrounding streams during an irrigation season were simulated with MODFLOW with its streamflow routing capabilities as documented by Prudic (1989). A better understanding of the coupled system was instrumental in elucidating, at least partially, the impact that the different water uses have on the hydraulic behavior of the groundwater system of the island.

Study area

Location and Physiography

The Rio Negro, in the Argentinean Patagonia, originates at the confluence of the Neuquén and Limay rivers (Fig. 1). These two tributaries drain an area of about 88,650 km^2 that occupies a wide mountain front along the Andes range, where the drainage network is exceedingly intricate. At their headwaters, the annual average precipitation either as rain or snow exceeds 1,000 mm and can reach up to 3,500 mm in places.

After traversing the Upper Valley, the Rio Negro enters the gently sloping Middle Valley to continue through the Lower Valley toward its outlet in the Atlantic Ocean.

The Middle Valley is divided into four subareas. The northern margin encompasses 50,000 ha between the Rio Negro to the south and the Patagonian Plateau to the north. The Choele Choel Island lies at the bifurcation of the Rio Negro into its North and South branches. The island is approximately 40 km long with a maximum width of 15 km, and encompasses around 34,000 ha, including Chica Island and other small islets. The southern margin of the Middle Valley lies between the South Branch of the Rio Negro and the irrigation diversion channel. The eastern Middle Valley extends downstream from the Choele Choel Island to the beginning of the Lower Valley, encompassing 70,000 still unexploited hectares. These four subareas are indicated in Fig. 2.

The focus of this work is Choele Choel Island. Its longitudinal slope is 0.58 cm per km. In the transverse direction, the island slopes gently from the South Branch toward the North Branch.

Hydroclimatic conditions

Summer temperatures average 23°C during January, while winter temperatures average 6.8°C. Maximum temperatures of 30°C are common in the summer months. Below freezing temperatures occur in June, July and August. The average annual precipitation is 303 mm. Rainfall is unevenly distributed in space and time, as is typical in semiarid climates. Strong winds frequently blow across the study area. The average wind velocity is around 10 km/h from May to July, and increases to 14–16 km/h from October to February.

DOI 10.1007/s10040-005-0472-3

Fig. 2 Physiographic regions – Stream stage stations: name and location

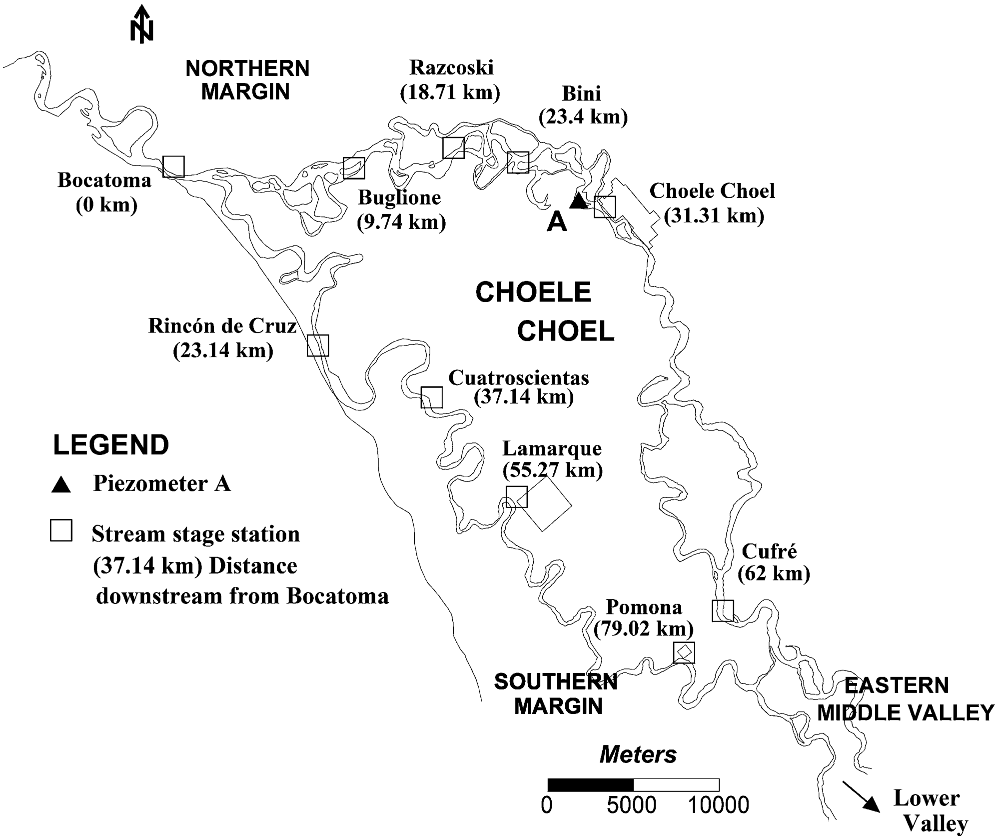
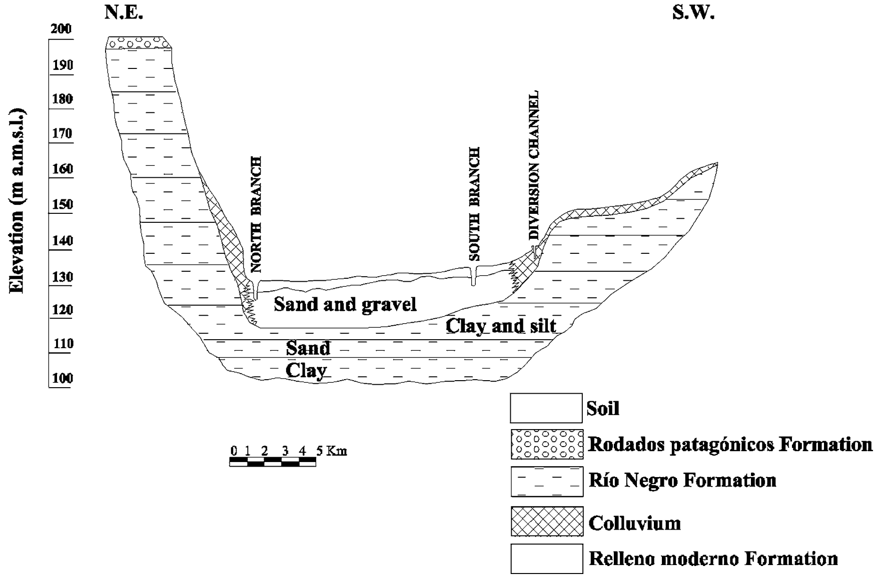


Fig. 3 Stratigraphic profile across the Choele Choel Island



Hydrogeologic setting

The Middle Valley was carved in the Patagonian Plateau by glaciers. Three geologic units form the Valley's stratigraphic profile (Fig. 3): (1) Río Negro Formation (Rionegrense): the lowermost portion of the profile, composed by alternate layers of sand, silt and clay of moderate to low permeability. Despite the fact that this geologic unit can reach several hundred meters in thickness, it is of little hydrogeologic interest; (2) Rodados Patagónicos: composed of conglomerates and boulders, usually cemented with calcium carbonate. These beds vary in thickness from 3 to 5 m and extend over all of the terraces surrounding the valley; (3) Relleno Moderno: overlies the Rionegrense in the valley center. It is mainly composed of a thin layer of silty sand, underlain by gravel deposits with variable quantities of sand and is characterized by high permeability. This is the main water-bearing unit of the profile. Unconfined in most of the area, it is highly dynamic and interacts closely

DOI 10.1007/s10040-005-0472-3

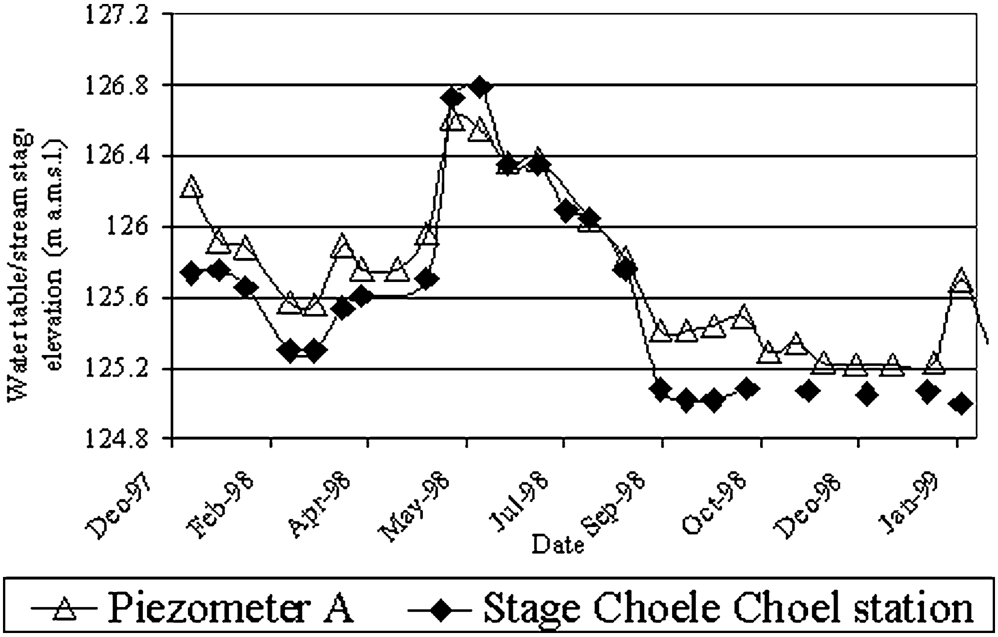


Fig. 4 Relationship between the stream stage at Choele Choel station and the water table elevation at a selected piezometer

with all surface water sources and sinks. Transmissivity values for this aquifer range from 200 to 2,500 m^3/day/m, while reported values for specific yield vary between 0.01 and 0.2. Field studies have shown that there is no hydraulic connection between the Relleno Moderno and the underlying formation (Interconsul-Tahal-Ade 1974).

Hydrology

The Rio Negro discharge is largely controlled by a series of dams located about 250 km upstream from the study site. The North Branch conducts more than 90% of the upstream flow. Both branches act as natural drainage canals, providing over 155 km of stream-aquifer contact that allows free groundwater drainage. The South Branch is a highly meandering stream approximately 87 km long, while the North Branch is 68 km long. The names and locations of the stream stage stations, four on the South Branch, and five on the North Branch, correspond to the cumulative distance from Bocatoma, as indicated in Fig. 2. Natural flow conditions in the Rio Negro have been altered by construction of hydroelectric power plants in the Limay and Neuquén rivers in the 1970s. Dam operation has modulated natural flows by decreasing peak flows and increasing low flows.

A total of 73 km of drain tiles and ditches of different sizes remove excess water accumulated during the irrigation season. Drainage water is then discharged at downstream locations along both river branches. Regulations govern maximum dam releases during the peak of the irrigation season to allow drainage of agricultural lands at downstream locations along the valley. Nonetheless, a failure to consistently enforce those regulations results in backwater effects at the discharge points of major drains, and subsequent elevation of the water table in vast areas of the island when stream stages are high. Irrigation water enters the island through an unlined 19-km-long channel, starting at the western corner of the island, 3.5 km downstream of the bifurcation point in the Rio Negro branches. Eight secondary unlined channels (89.8 km long), and minor channels that reach outlying irrigated fields (61.2 km long) complete the irrigation network. Irrigation is by gravity, with an application frequency of about two to three weeks, on average.

Groundwater fluctuates in response to river-aquifer interactions; evapotranspiration losses from crops and riparian vegetation; groundwater flow to drains; losses from unlined irrigation channels; and percolation at irrigated fields. Figure 4 shows the stream stage at the Choele Choel station and the groundwater elevation at piezometer A indicated on Fig. 2. The graph was constructed with data from a recording period that overlaps with part of the modeling period. Water table elevations were collected every 15–20 days. Stream stages were recorded daily. For consistency, daily stream stages between two consecutive water table readings were averaged and the resulting average plotted with the second of the water table readings. Groundwater elevation follows stream stage fluctuations very closely, in particular during the non-irrigation period from April to late August. Irrigation-derived recharge has a marked influence on the peaks of January 5, 1998; March 23, 1998 and January 2, 1999 (see Fig. 4).

Evapotranspiration constitutes an important loss from the groundwater system. Luque et al. (1970) applied the Blaney-Criddle method (Blaney and Criddle 1950) to estimate consumptive uses for different crops on the island. Since the most recent agriculture census on the island was conducted in 1995, any crop-related computations are very approximate. The values of consumptive water use by crops listed on Table 1 result from a weighted average considering the area covered by the prevailing crops, namely pears, peaches, apples, plums, tomatoes and potatoes. Water demand by crops is much smaller than the irrigation water diverted at the origin of the main channel.

DOI 10.1007/s10040-005-0472-3

Table 1 Consumptive use (CU) and water derived for irrigation

Month	CU		Irrigation water (m^3/s)
	(mm/month)	(m^3/s	
Jun-98	0.0	0.0	0.00
Jul-98	0.0	0.0	0.00
Aug-98	33.1	0.2	21.30
Sep-98	34.4	0.9	25.40
Oct-98	35.2	1.1	25.20
Nov-98	113.1	3.8	27.10
Dec-98	163.2	5.2	27.60
Jan-99	181.6	5.8	27.50
Feb-99	136.5	4.8	26.00
Mar-99	96.0	3.1	27.00
Apr-99	41.2	1.4	27.20

Methods

MODFLOW was used to simulate groundwater flow and to investigate the stream-aquifer relationship. The island was discretized with a uniform rectangular grid of 134 rows and 64 columns oriented in the direction of the regional groundwater flow. Cell size was set at 300×300 m. A single layer representing the Relleno moderno Formation with a constant thickness of 20 m was considered. The aquifer was simulated as a free-surface boundary able to fluctuate in response to recharge from irrigation fields, evapotranspiration, losses from unlined irrigation canals, flow to drains and interaction with streams. The North and South branches of the Rio Negro were represented by 197 and 244 nodes, respectively (Rodríguez et al. 2002). River branches were defined as variable head boundaries in the periphery of the island, modeled by means of MODFLOW's STREAM package. In the southeast extreme, between the North and South branches, a time-variable constant head boundary was adopted, in accordance with the changing hydrologic conditions of the system during the irrigation season. Flow to drains was simulated through the MODFLOW DRAIN package. Main drain canals were represented by 266 cells which closely followed the real location of the drainage network. Figure 5 illustrates drain, stream, irrigation channels and constant head nodes. The grid has been omitted for the sake of clarity.

Table 2 Streamflow input to the model (*NB*: North Branch; *SB*: South Branch)

Month	Streamflows (m^3/s)	
	NB	SB
Jun-98	990	110
Jul-98	749	83
Aug-98	429	48
Sep-98	229	33
Oct-98	336	37
Nov-98	333	37
Dec-98	359	40
Jan-99	339	38
Feb-99	244	27
Mar-99	218	24
Apr-99	209	23

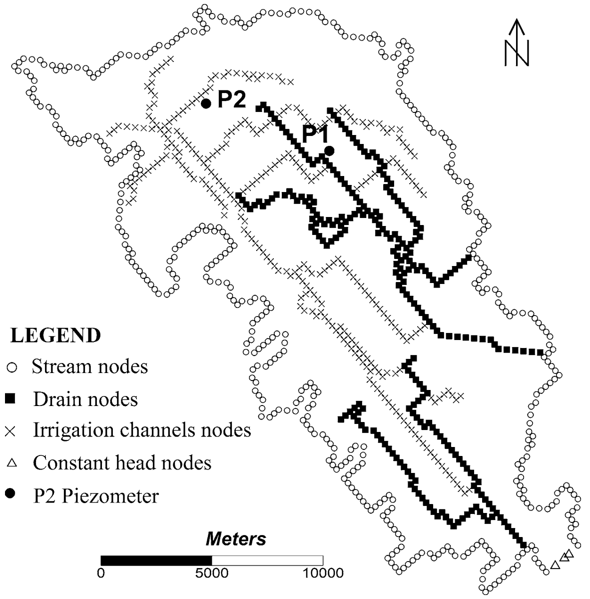


Fig. 5 Discretization of the groundwater model sinks/sources and boundary conditions

Model calibration

Model calibration was achieved through the classic trial-and-error procedure, by matching simulated heads with observed heads and simulated stream stages with observed stream stages. First, a steady-state simulation was conducted to obtain both a set of calibrated parameters and initial conditions for the transient simulation. June of 1998 was defined as the steady-state month. In that month, as in every June, most of the groundwater accumulated in saturated storage during the preceding irrigation season had been evacuated through drains and rivers. The transient run spanned a complete irrigation season from July 1998 through April 1999, with a monthly stress period. Streamflows from an upstream gauging station located on the Rio Negro were distributed between the two branches by means of a partition coefficient to define the streamflow input to the model based on the distribution observed in field data. Table 2 includes streamflow input to the model for both river branches in the steady-state case and the transient case.

Steady-state simulation

In June, only streams and drains were active as sinks/sources. Calibration parameters included hydraulic conductivity K, Manning's roughness coefficient n, drain stage h_d, drain conductance C_d and streambed conductance C_s. Initial estimates for the parameters were either extracted from previously published studies (Interconsul-Tahal-Ade 1974), from field data supplied by the State Water Authority, or by adjustment during calibration if no previous

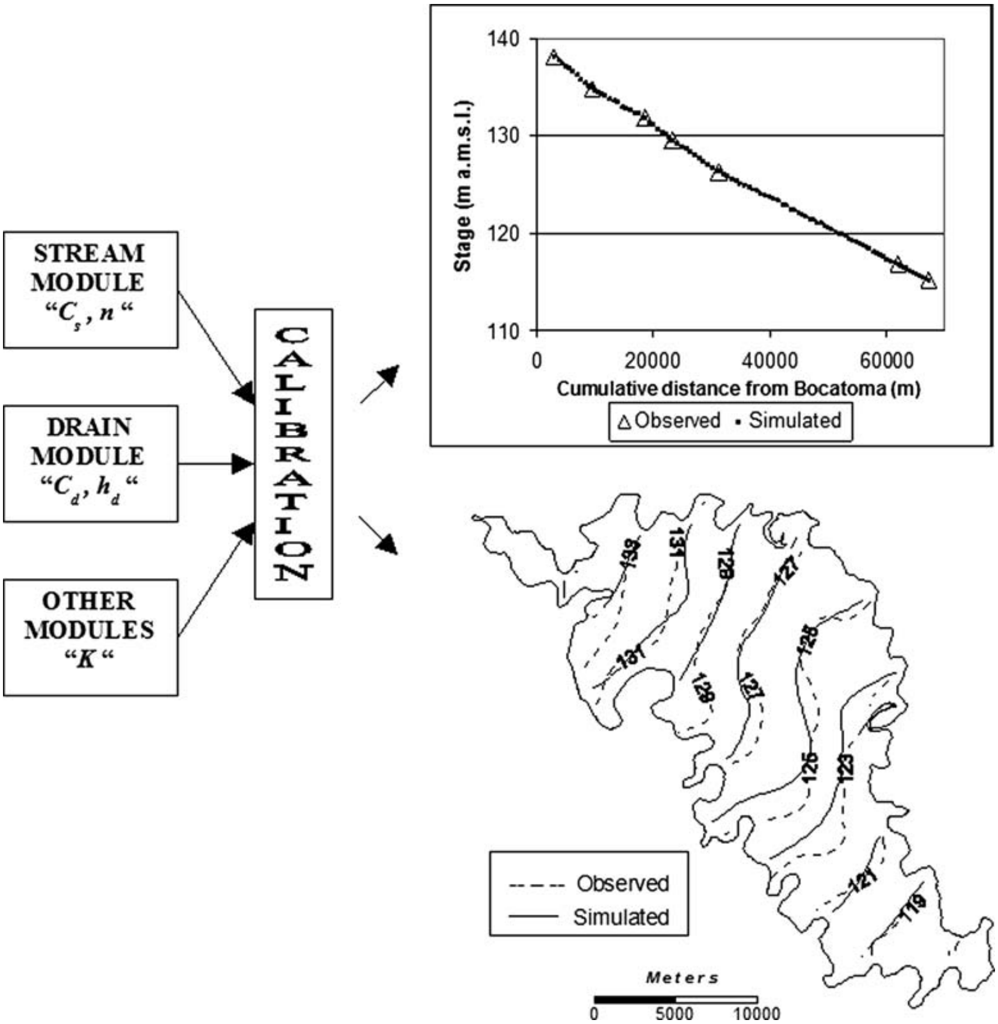


Fig. 6 Steady-state simulation (June 1998): schematic of active MODFLOW modules and calibration parameters. Comparison between simulated and observed stream stages along the North Branch and between simulated (*solid*) and observed (*dashed*) aquifer head (contour interval: 2 m)

information existed. Figure 6 shows the MODFLOW packages representing sinks and sources during the simulation along with the calibration parameters.

Hydraulic conductivity values derived from aquifer tests ranged from 38 m/d up to 345 m/d. Field data were concentrated on the periphery of the island, and no prior estimates existed at the island center. Model calibration yielded a minimum hydraulic conductivity of 17 m/d and a maximum of 860 m/d, with the latter occurring in a small area at the island center.

Information on the drainage system was very scarce. Consequently, a physically sound set of parameter values was selected in order to match observed aquifer heads. After some preliminary testing, water depth in the drains was set at 0.30 m. At the outlets of main drain canals into the streams, drain stages were varied to ensure hydraulic continuity. Calibrated values for drain conductance ranged from 0.003 m^2/s to 0.0068 m^2/s.

Manning's roughness coefficient influenced mass balance computations within the STREAM package. Its calibrated range was 0.025 to 0.06. These values agree with previously published data (Interconsul-Tahal-Ade 1974). Few values for streambed conductance are reported in the literature, therefore it is usually determined in the calibration process. In this case, calibrated streambed conductances ranged between 1.1 m^2/s and 10.71 m^2/s.

Contour lines constructed from water table elevations (meters above msl) recorded at 118 piezometers and from simulated aquifer heads compared fairly well for the steady-state month. The agreement was good in the central portion of the island and all along the North Branch, however results showed some discrepancies in the vicinity of the South Branch, where field data were less reliable. Similarly, simulated water surface profiles along both streams reproduced observed data quite satisfactorily (Rodríguez et al. 2002). The calibration target for stream stage was set at ±0.12 m. The mean absolute value of the difference between observed and simulated stream stage at both river branches was 0.05 m. Steady state results are shown in Fig. 6.

Transient simulation

Model complexity increased as new sinks and sources, namely losses along irrigation channels and effective recharge, were introduced. Initial values for groundwater levels and stream stage were those generated through the

DOI 10.1007/s10040-005-0472-3

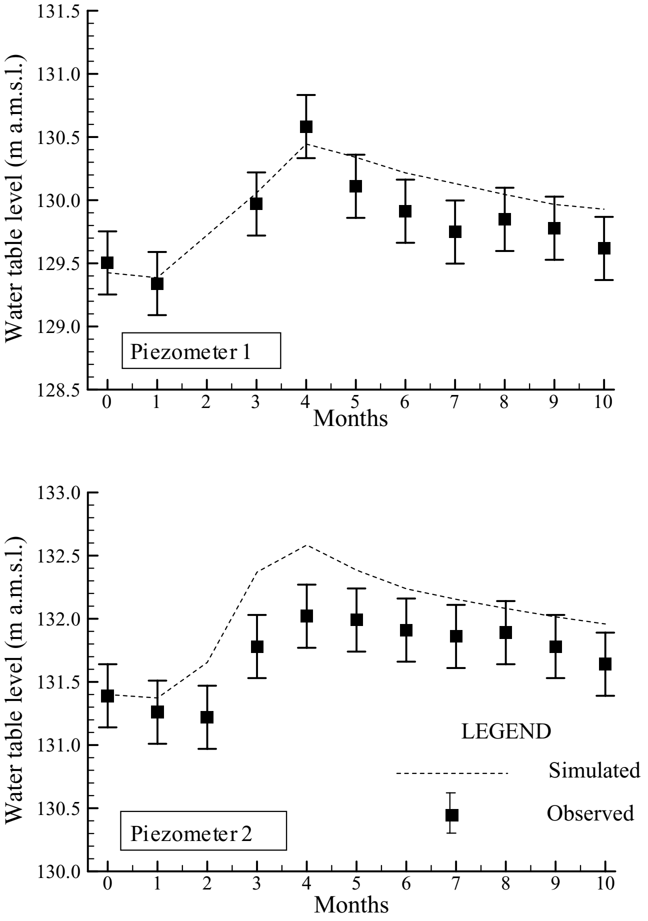


Fig. 7 Simulated and observed water table elevation at two selected piezometers (shown on Fig. 5) (Note: month 0 corresponds to June 1998)

steady-state simulation. Manning's roughness coefficients and drain conductances were held constant, water depths along drains and streambed conductances were modified according to changing hydrological conditions throughout the simulation. Calibrated specific yield values fell between 0.02 and 0.06.

Transmission losses from irrigation channels were initially estimated from field data and later refined for each simulated month. The total simulated volume added to the aquifer from this source was around 63×10^6 m^3. Previous estimates (Interconsul-Tahal-Ade 1974) were on the order of 80×10^6 m^3, however this value also includes losses through numerous tertiary irrigation channels not explicitly represented in the current model.

Instead of implementing the MODFLOW RECHARGE and EVAPOTRANSPIRATION packages separately, areal recharge at irrigation fields and evapotranspiration losses from crops and riparian vegetation were combined in a single effective recharge rate, R_e used in the RECHARGE package. Losses along tertiary distribution canals were also embedded in this effective rate. The magnitude of R_e was allowed to vary in space and time in order to fit model results to observed water table elevations. The maximum R_e was applied in September, coinciding with the sudden increase in aquifer head registered at the piezometers, as explained below. Figure 7 illustrates simulated and monthly average observed water table elevations at two selected piezometers whose locations are indicated in Fig. 5. The 0.50-m high vertical bar centered at observed values represents the calibration target (set at ±0.25 m). Notice that month "0" indicates June 1998. The figure illustrates that water levels rise considerably between August and September, at the beginning of the irrigation season, and decrease very slowly afterwards. In most of the piezometers, simulated water levels were within the calibration target. Stream-related data were not as good as groundwater level data, though all records contained data gaps. Figure 8 shows simulated hydraulic profiles along the North Branch as well as hydraulic profiles interpolated from stream stage stations. In general the agreement was good in both branches. Comparison with field data was possible only through January 1999 as no stream stage readings were made afterwards. Judgment of calibration acceptability took data quality into account.

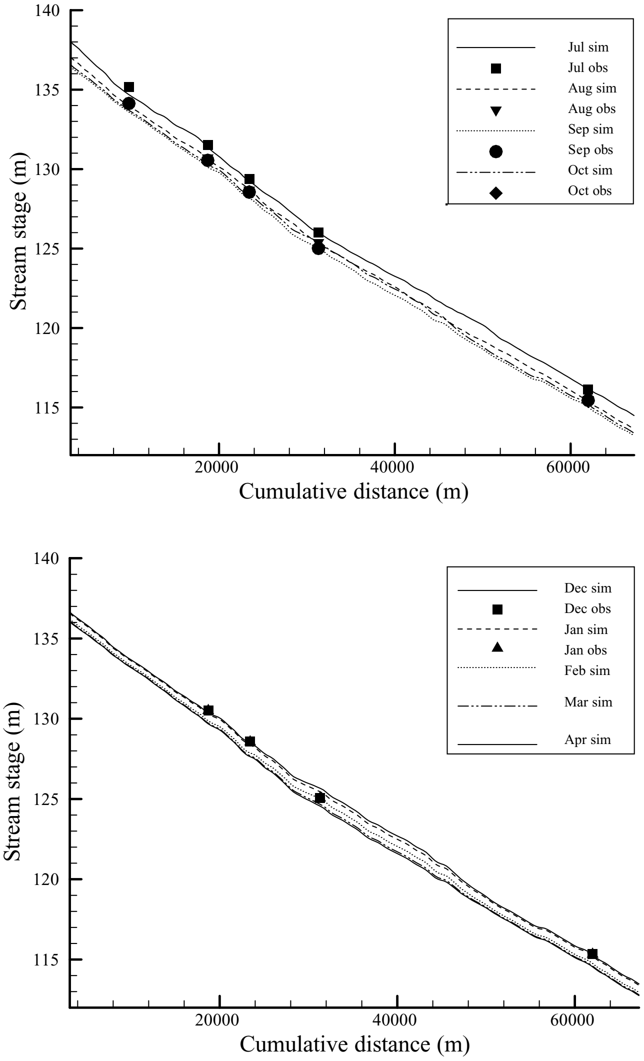


Fig. 8 Simulated/observed hydraulic profile along the North Branch

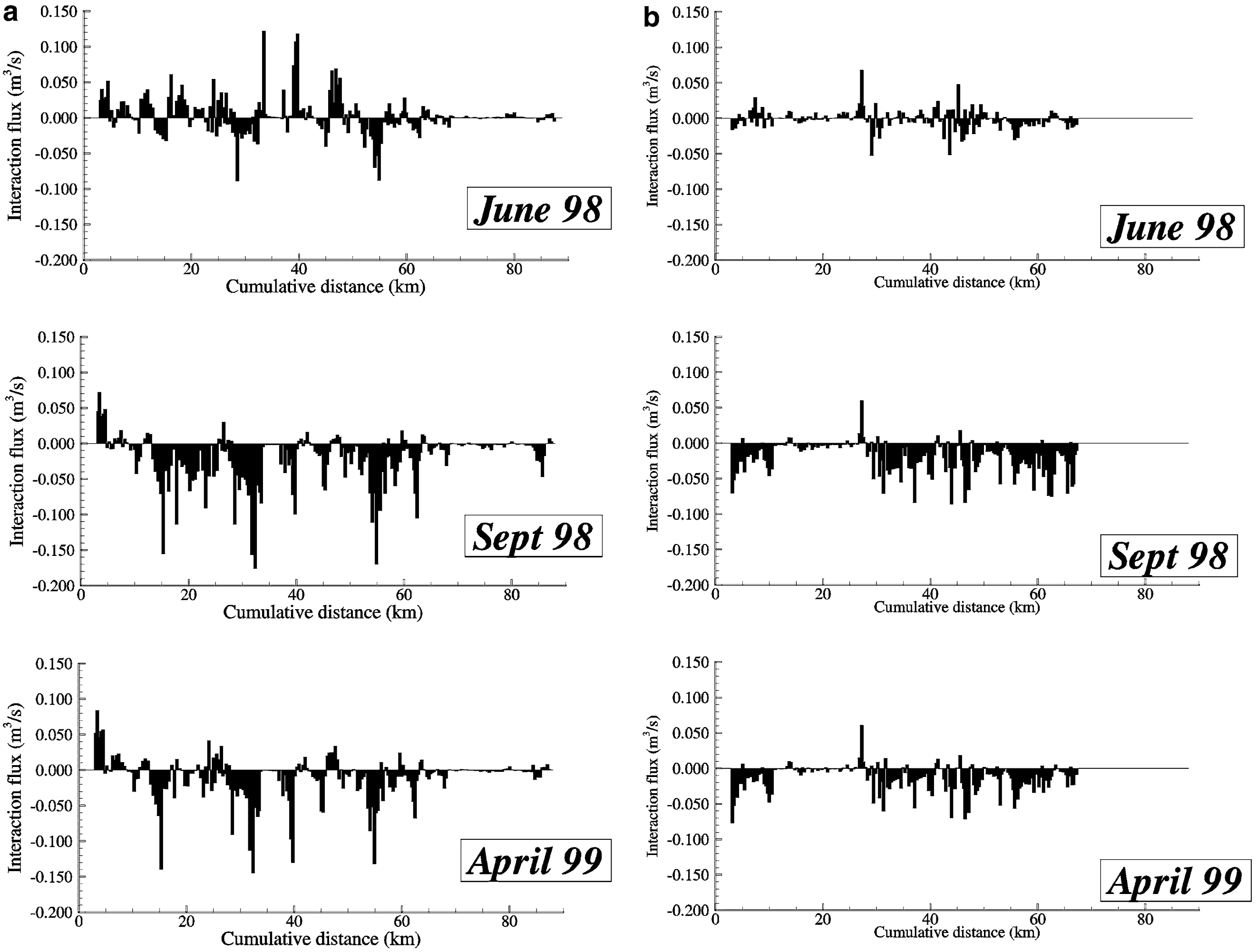


Fig. 9 **a** Simulated stream-aquifer fluxes for selected months – South Branch. **b** Simulated stream-aquifer fluxes for selected months – North Branch

Discussion of stream-aquifer interactions results

Whereas many stream-aquifer investigations are motivated by groundwater pumping-induced depletion in predominantly groundwater-fed streams, in the present study area, water for irrigation is obtained from streams. The problem investigated here stems from the fact that occasional high stream stages during the irrigation season prevent the free drainage of irrigated lands, thereby causing water table mounding which, in turn, affects agricultural production.

Groundwater on the island is lost through evapotranspiration and is discharged directly into both river branches and into the artificial drainage network as return flows. Although no field surveys exist to quantify return flows, modeling results support some previous estimates by agricultural engineers that groundwater discharge into streams is one order of magnitude higher than groundwater discharge to drainage canals. In fact, the maximum simulated stream-aquifer flux reached -7 m^3/s, while the maximum simulated flow to drains was -0.78 m^3/s. These values correspond to an October 1998 Rio Negro streamflow of 448 m^3/s.[1] On the one hand, the above situation is favored by the considerable length of stream-aquifer contact which, in combination with low stream stages, provides a suitable hydraulic gradient to discharge excess groundwater. On the other hand, drain conveyance capacity is severely reduced in places due to poor maintenance. In addition, occasional high stream stages during the peak of the irrigation season may cause backwater effects at drainage canal outlet points, precluding the free discharge of drain flows into streams. Therefore, keeping stream stages low is key to discharging excess groundwater.

A transverse profile of piezometric data across the island during non-irrigation months shows that, in general, the transverse flow direction is from the South Branch to the North Branch. On average, the South Branch is a losing stream in June–July, while the North Branch is a gaining stream year round. This pattern is illustrated by the simulated stream-aquifer interaction fluxes listed in Table 3. Notice a positive flux for the months of June and July for

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[1] Note that the MODFLOW sign convention has been adopted (i.e., negative fluxes represent losses from the aquifer, positive fluxes represent gains to the aquifer).

Table 3 Simulated stream-aquifer interaction flux (*NB*: North Branch; *SB*: South Branch)

Month	Interaction flux (m^3/s)	
	NB	SB
Jun-98	−0.27	0.62
Jul-98	−1.10	0.08
Aug-98	−2.22	−0.94
Sep-98	−3.64	−4.56
Oct-98	−2.98	−4.01
Nov-98	−2.89	−3.89
Dec-98	−1.92	−2.48
Jan-99	−2.24	−2.44
Feb-99	−2.90	−2.89
Mar-99	−2.63	−2.53
Apr-99	−2.34	−2.32

the South Branch, indicating losses to the aquifer according to the MODFLOW convention sign explained above. In August, when irrigation begins, the water table starts rising, hydraulic gradients along the South Branch reverse and this branch switches from a losing stream to a gaining stream.

The system dynamics can also be visualized by means of a qualitative analysis of the seasonal variations in stream-aquifer fluxes along each branch. Figure 9a shows stream-aquifer fluxes for June 1998, September 1998, and April 1999 along the South Branch. These periods represent, respectively, a non-irrigation month, soon after irrigation begins, and the end of the irrigation season. In June, losing and gaining reaches of the stream alternate except in the last 15 km downstream, where hydraulic gradients between the stream and the adjacent aquifer are usually low throughout the year. This area suffers recurrent flooding, the precise causes of which are still under investigation. Upstream from this region, the model indicates a remarkable change in stream-aquifer fluxes due to the combined effects of irrigation and stream stage variations. The sudden rise in groundwater levels at the beginning of the irrigation season, in conjunction with relatively low stream stages during the simulation, induces a rapid increase in hydraulic gradients and thus an increase in flux flows. Most losing stream reaches turn into gaining reaches, while those that maintain their gaining character experience increased exchange flux rates. This situation is evident for the month of September 1998. For April 1999, stream-aquifer interactions followed the pattern of previous months, however the magnitude of the flux started to decrease as the irrigation receded. Simulated stream-aquifer fluxes along the North Branch are depicted in Fig. 9b. In general, they show a similar pattern to those modeled for the South Branch, except that a low-interaction zone is identified at the beginning of the study reach. At this location, observed and simulated groundwater contours were approximately perpendicular to the stream, indicating very small stream-aquifer gradients.

Low-priced irrigation water, resulting in careless irrigation practices, leads some farmers to irrigate excessively. Losses through unlined distribution canals and in irrigated fields cause unwelcome water-table mounding in some locations. Moreover, high stream levels caused by hydroelectric power generation from upstream dams during the peak of the irrigation season interfere with groundwater discharge into streams and drain canals. Farmers along the Middle Valley of the Río Negro blame hydroelectric power companies for high groundwater levels at their farms, while power companies claim that inefficient irrigation practices are the actual cause of the problem. Both parties contribute to the situation.

Once satisfactorily calibrated for a historical period, the model was used to isolate the effect of high stream stages on groundwater levels. To that end, a synthetic simulation was set up taking into consideration the worst-case scenario (i.e. groundwater levels at their highest). This situation occurred in October 1998, at a Rio Negro streamflow of 448 m^3/s. Simulated groundwater levels for this month were defined as the initial condition for the synthetic simulation. Then, a sudden increase of the Rio Negro streamflow, from 448 m^3/s to 1,100 m^3/s, was introduced until the model reached a new state of equilibrium. All other variables and parameters remained unchanged. A river discharge of around 500–550 m^3/s is considered a threshold for impeding the normal discharge of groundwater during irrigation periods. Streamflows above this value start interfering with the normal discharge of excess groundwater accumulated on the island. Doubling the threshold streamflow would give the State Water Authority a qualitative indication of an extreme condition for irrigated lands along the valley.

The difference between the initial and final simulated aquifer heads was calculated for each cell and plotted in Fig. 10. The effect of an increase in streamflows, and hence in stream stage, radiated toward the interior of the island, gradually fading until it disappeared completely. Water

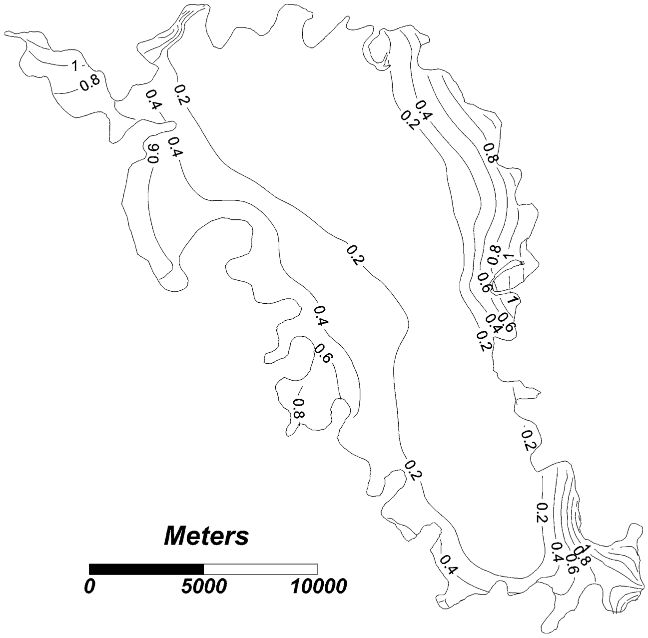

Fig. 10 Simulated effect of a sudden streamflow increase on groundwater levels. Isopleths show water-level rise in intervals of 0.2 m

DOI 10.1007/s10040-005-0472-3

level increases were highest along the periphery of the island, where water levels rose more than 1.5 m in 5.14% of the area. The levels in 22.65% of the island remained unaffected. The average water table increase in the affected area was 0.25 m. Even though this is a qualitative analysis and percentages are only indicative, the penetration of stream floods into similar alluvial aquifer systems in irrigated areas along the Upper Rio Negro Valley has been observed in field data (Rodríguez et al. 1998). At present, groundwater levels are being monitored on a continuous basis at several strategic locations around the island in order to improve the knowledge of the stream-aquifer relationship and for the purpose of improving model simulations and predictions.

As explained previously, irrigation also contributes in many ways to raising groundwater levels. Even though this topic is not the main focus of this work, some comments are merited. Table 1 included consumptive water use calculated by the Blaney-Criddle formula (Blaney and Criddle 1950) and irrigation water gauged at the origin of the main irrigation channel. In actuality, the amount of water diverted for irrigation is enough to water more than twice the current irrigated area. Given the fact that the size of the irrigated area is fairly constant throughout the irrigation season, a simple comparison between estimates of consumptive use and actual irrigation water shows excess water in the system. While irrigation water use shows little variation through time, the crop demand differs greatly from month to month. Therefore, the unused water in excess of that directly discharged into drainage canals accumulates in the alluvial aquifer causing water table build-ups. In fact, high values of effective recharge in September and October were necessary in the model to overcome the gap between consumption and delivered irrigation water.

Summary and conclusions

Whereas many stream-aquifer investigations are motivated by surface water depletion attributed to groundwater withdrawals for irrigation, in the situation discussed here water for irrigation is extracted directly from streams. Unwelcome groundwater accumulation and drainage problems on the Choele Choel Island have resulted in conflicts between water users, namely farmers and hydroelectric power plant operators.

A groundwater/surface water interaction model was constructed with the aim of getting a better understanding of the system dynamics. The MODFLOW-based modeling approach provided valuable insight to the problem.

Model calibration was achieved through the classic trial-and-error procedure. A steady-state simulation provided a set of calibrated parameters and initial conditions for a transient simulation. The transient simulation extended through a historical irrigation season and utilized a monthly stress period. The model was calibrated by matching simulated heads with observed heads and simulated stream stages with observed stream stages. Results were considered reasonably good, considering the quality and quantity of available field data.

Model results have shown that natural drainage through stream branches is the leading mechanism for discharging groundwater accumulated in the alluvial aquifer during the irrigation season. The sudden rise in groundwater levels at the beginning of the irrigation season, in conjunction with relatively low stream stages during the transient simulation, caused a rapid increase in hydraulic gradients and thus an increase in the interaction flows (fluxes). Most losing reaches of the stream converted to gaining reaches, while those that maintained their gaining character experienced increases in the magnitude of stream/aquifer interaction fluxes. This behavior was common to both river branches.

A synthetic run was designed to simulate a sudden increase in streamflows above the recommended threshold during the irrigation season. Though qualitative in nature, the results of this simulation indicated the potential effect of high stream stages on the groundwater system during the peak of the irrigation season.

Surface water losses from unlined irrigation channels and inefficient irrigation practices contribute to increased groundwater levels. Therefore, efforts should be made to reduce irrigation water allocations and to gradually switch to more efficient irrigation practices. In addition, existing regulations regarding dam releases (i.e., threshold streamflows), should be enforced in order to maintain low stream stages during critical months. Together, these two measures could substantially reduce excessive water table rises on the island. At present, groundwater levels are being monitored on a continuous basis at strategic locations. As more data become available, the numerical model can be upgraded in order to improve its calibration and prediction capabilities.

Acknowledgments The authors are grateful to the Negro River State Water Authority (SWA) for providing partial financial support for the project and all the necessary field data for the study. In addition, they would like to thank two anonymous reviewers whose comments enhanced the report. Dr. Laurel Lacher, consulting hydrologist, kindly reviewed the manuscript and made really valuable suggestions.

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DOI 10.1007/s10040-005-0472-3