

Sustainable Groundwater Management Concepts & Tools

Case Profile Collection Number 6

Argentina: Integrated Approaches to Groundwater Resource Conservation in the Mendoza Aquifers

2002-2005

Stephen Foster & Héctor Garduño

Task Manager: Alvaro Soler (World Bank - LCR)

Counterpart Organization: Mendoza State - Direccion General de Irrigacion (DGI)

This case profile relates to advice provided to the DGI-Mendoza (the state water regulatory agency) in support of their technical and institutional efforts to conserve and protect critical groundwater resources in an arid region – the work having been undertaken in liaison with the provincial environmental ministry (MAyOP). In two important areas, salinization processes are threatening the naturally high-quality of groundwater and causing serious concern about impacts on salinity-sensitive commercial vineyards and fruit orchards. More locally oilfield operations and petroleum refining pose an additional threat to groundwater quality, and could also compromise its suitability for potable water-supply. Extensive data on these issues have been published and/or provided to GW•MATE by the DGI-Mendoza, Instituto Nacional del Agua (INA) – CRA, CELAA & CRAS offices, and GW•MATE was mobilized under the general umbrella of the World Bank/Inter-American Development Bank PROSAP programme, which has a DGI-Mendoza ‘Calidad de Agua y Suelo’ Component, and was also helped by GWP-SAMTAC in defining the work reported here.

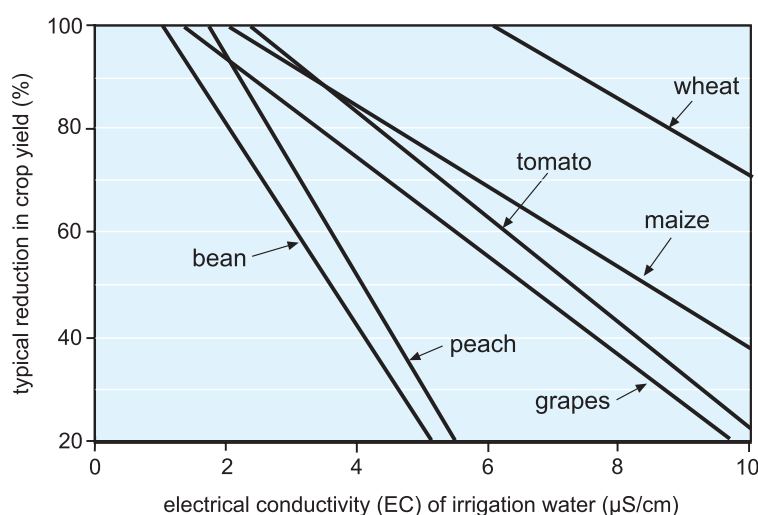
A: REVIEW OF GENERAL APPROACHES TO GROUNDWATER MANAGEMENT

- The DGI takes a proactive approach to water resource provision for the development of irrigated agriculture and urban water-supply, and are attempting to integrate groundwater more consistently into the hydraulic infrastructure and water resource planning, which has a long history. This has been facilitated by the fact that DGI is a single autonomous water resource authority, which maintains good hydrological records and agricultural water-use data.
- The initial approach to groundwater resource management was:
 - to encourage irrigation well drilling (where feasible) in areas outside the command of existing surface water canals
 - to permit well drilling in areas where existing canals could not provide a reliable supply during periods of minimum surface water flow and maximum plant water demand.

But this strategy has encountered problems in some areas, where aquifer behavior has been different to that expected. In particular increasing trends in salinity have developed in two areas of intensive groundwater irrigation, which are impacting productivity (Figure 1) in the vineyards and orchards (of export quality) across the area.

- An important component of the overall groundwater resource management strategy is a detailed (GIS-based) survey of existing surface water and groundwater use rights and irrigation practices (Figure 2), as a basis for knowing the water users, understanding the incentives to which they respond, and thus facilitating their greater involvement in resource management.

Figure 1: Sensitivity of a range of crops to irrigation water salinity



- It should be noted that the local socio-economic characteristics of water resource use are relatively unusual in that:
 - groundwater users include a high percentage of recently-established major international producers using modern high-efficiency irrigation methods
 - amongst surface water users, long-standing smallholders using traditional low-efficiency irrigation techniques dominate

and the reallocation of water resources from the latter to the former in the interests of aquifer management tends to encounter opposition on grounds of 'property rights' and general social friction. However, financial facilities have been sought for the modernization of existing irrigation to pressurized systems (with drip and micro-spray application), where feasible in return for reductions in water use rights.

Groundwater Use Restriction Zones

The strategy of introducing 'groundwater use restriction zones' in areas of increasing salinity should be viewed as a useful contribution to groundwater resource management, because it has permitted control of groundwater abstraction whilst still allowing:

- construction of more energy-efficient wells (of equal yield and use) as replacement for existing wells (providing these are sealed)
- reallocation of groundwater resources to high-value uses by purchase and sealing of existing wells (the purchase price having locally exceeded US \$ 10,000) with construction of close-equivalents at new locations within the same zone – this despite the fact that trading of water rights is not permitted by provincial water law
- there is a clause in provincial water law requiring ‘beneficial use’ and not allowing stockpiling of groundwater abstraction rights.
- The ‘sale’ of excess surface water allocations (but not of rights) is also permitted (with DGI as intermediary), but with the local cost of irrigation modernization running at about US\$1000/ha this does not generally appear to represent a strong enough incentive for surface water irrigators to invest in water-saving measures. Moreover, the DGI still lacks adequate legal powers and/or financial resources to:
 - transmit excess surface water (where available) to areas without rights
 - reduce rights in riparian areas of inefficient water use.

Abstraction Measurement & Charging

- The existing system of legal rights for groundwater abstraction and use in Mendoza stipulates an annual water resource charge based on well diameter (as a surrogate for potential installed pump capacity), but no distinction is made on grounds of efficiency of the irrigation use nor the level of water-stress in the area concerned. The DGI could generate considerably increased revenue with a better level of fee collection, and even more with differential charging in critical areas (such as the groundwater use restriction zones). This could provide finance to rectify local resource problems and to intensify study of problematic areas.
- The capital cost and operational difficulty of using water meters to make direct measurements of groundwater pumped by irrigation wells (unless specifically requested and maintained by users) has deterred their installation. However, a full-scale pilot project has been carried out, with the collaboration of EDEMSA (the privatized electrical energy utility), to explore the scope for using rural electricity consumption meters to support the regulation of groundwater abstraction. This requires a major effort to consolidate (on a GIS platform) the inventory of irrigation wells, to cross-reference each well with the corresponding electricity meter, to correlate groundwater use with electricity consumption (and how this varies with well and pump condition), and to map land-use in terms of cultivated area and those fields irrigated wholly or partly with groundwater (Figure 2). This approach is showing considerable potential in terms of
 - identification of clandestine irrigation wells and excessive pumping from wells with existing abstraction rights
 - use of electricity bills for simultaneous charging of groundwater abstraction, on a basis of estimated actual use rather than potential capacity.

Figure 2: Detail of GIS-produced survey map of irrigation waterwells and groundwater use



- The issue of the provincial electrical energy subsidy is complex, although there is little doubt that in principle it could usefully be re-targeted. However, at present most users pay around 7 times more for groundwater than surface water for irrigation (Table 1) since:
 - historically all surface water irrigation infrastructure has either been wholly or partially subsidized depending on its level
 - groundwater users have to finance well drilling but do benefit from the provincial electricity subsidy
 - the level of collection of water fees (canons) is still not good for surface water users and very poor for groundwater users.

Table 1: Comparison of cost to users of groundwater and surface water for agricultural irrigation

COST COMPONENT	GROUNDWATER WELLS	SURFACE WATER CANALS
Permission to Construct	US\$ 20-40/a/well	not applicable
Water Resource Fee		US\$ 10-15/a/ha irrigated
Operation & Maintenance Costs	partly covered by DGI/WUA fee, but also allowed for below	some local costs included in DGI/WUA fee, but others met by local government
Capital Depreciation Allowance	allowed for in calculation below	hydraulic infrastructure provided by local government without cost recovery
Typical Equivalent Cost to Irrigator	US\$ 0.015/m ³ **	US\$ 0.002/m ³

* expressed as US\$ but based on costs in Argentina pesos in June 2002 with exchange rate of about 3.0

** after deducting subsidy of about US\$ 240/a

Water-User Participation in Resource Management

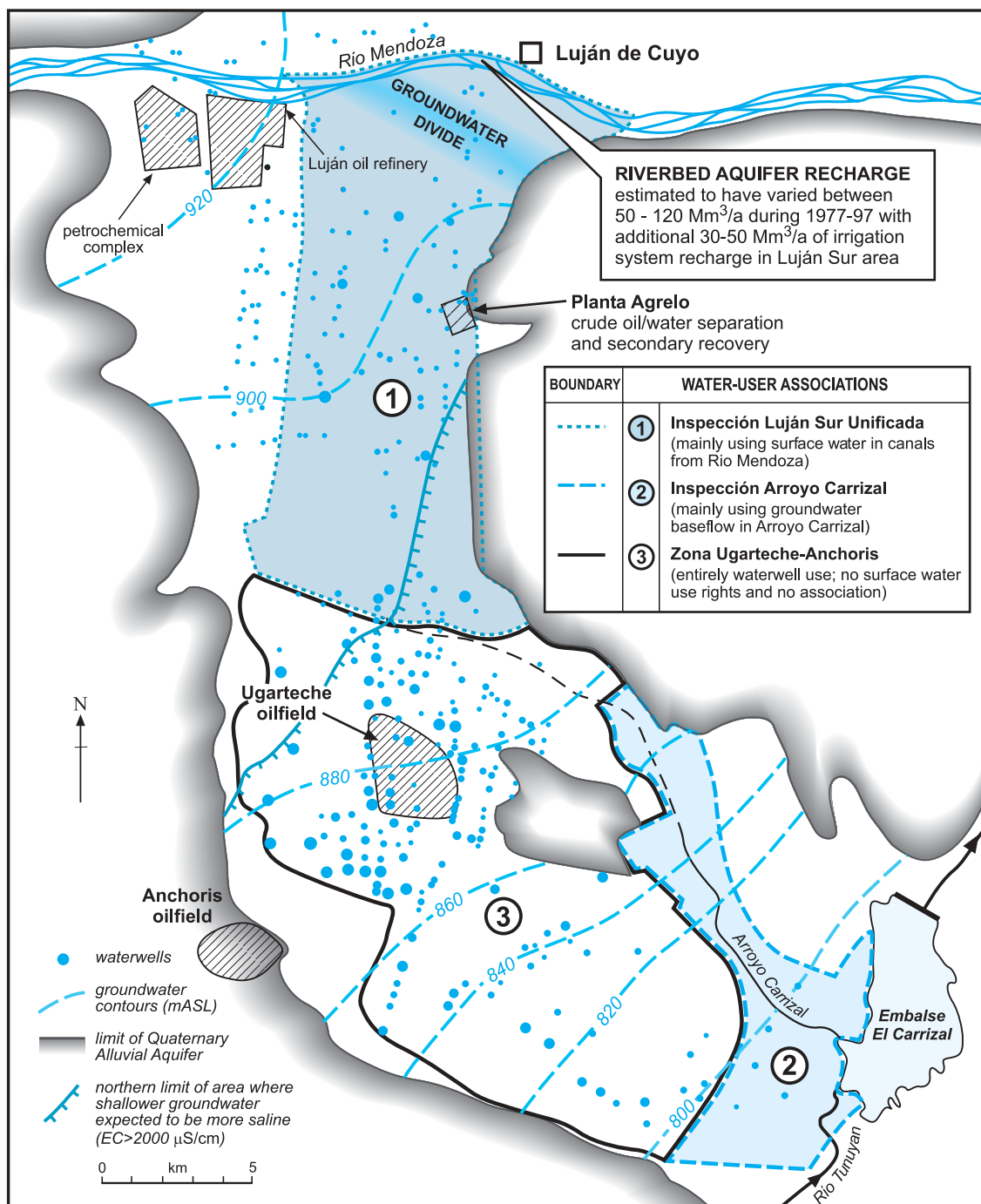
- Water-user associations (WUAs), known locally as ICs ('Inspecciones de Cauce'), based on the primary irrigation canal infrastructure, have successfully existed for some time. More recently transfer of some groundwater management responsibilities is under trial in pilot areas — including fee collection, water-use measurement and well inventory up-dating.
- However, there are some significant impediments to involving water-users more fully in groundwater resource management;
 - historically the WUAs are organized around primary irrigation canals and neither their territorial scale nor their boundaries are really suitable for aquifer management
 - there is reluctance by groundwater-only irrigators outside present WUA boundaries to join and contribute to the neighbouring WUA, since it is alleged there are no 'visible benefits' where groundwater is concerned
 - WUAs are not generally achieving a high level of fee collection and no mechanism has yet been established to sanction those ineffective in tasks assigned to them
 - there is danger of some WUAs becoming mainly a 'political lobby group' for the provision of subsidized surface water-supply.
- The preferred approach is thus to promote formation of an aquifer management organization (AMOR) for the sub-catchment, involving the groundwater users (preferably grouped into a new WUA), representatives of the existing WUAs, the public water-service company and other stakeholders. The existence of strong WUAs based on irrigation canals may prove a complication in this regard but one which it will be necessary to overcome. The existence of an AMOR will be especially critical to the development and acceptance of effective policies to control and to mitigate the effects of local groundwater pollution.
- However, It is accepted that on-going legal disputes for 'individual damage compensation' in some areas, and the intervention of the national legal adjudicator (Fiscalidad del Estado) have combined to produce a social climate in which it was difficult for DGI to promote community participation in groundwater management until an unequivocal and incontrovertible technical understanding of the status of groundwater quality had been generated.

B: RESOURCE MANAGEMENT AND QUALITY PROTECTION FOR THE CARRIZAL AQUIFER

Main Groundwater Resource Concerns

- The Carrizal Sub-Catchment, which occupies 240 km² of the Departamento-Luján de Cuyo, is a palaeo-valley located between the present courses of the Mendoza and Tununyan rivers (Figure 3). The northern part of the valley is filled with Quaternary piedmont deposits, which form an important unconfined aquifer of high permeability, but southwards these gravels thin abruptly (Figure 4), and the flowpath beyond to the Tununyan river is partly in a Tertiary (Mogotes) Formation.

Figure 3: Sketch map of the Carrizal aquifer system



- Natural groundwater recharge originates as infiltration over a 10 km stretch of the bed of the Río Mendoza and aquifer discharge creates the Arroyo Carrizal (a tributary of the Río Tunuyan). The rate of riverbed recharge (determined by differential gauging) varies considerably with riverflow regime, but it is estimated to have averaged 85 Mm^3/a during 1979-94, and around a further 40 Mm^3/a of river-water diverted for irrigation in the Luján Sur area is considered to end-up as groundwater recharge.

- A new dimension for groundwater resource management in the area relates to probable changes in riverbed recharge (both decreases and increases are possible), resulting from flow diversion for power generation at the new Potrerillos dam. The change in riverflow regime began in 2000 and full diversion commenced early in 2003 – this reducing the length of riverbed over which recharge to the aquifer continuously occurs by more than 60 %, but also produce ‘clear water infiltration’ conditions both in the riverbed and irrigation distribution system of the area.
- Traditionally the Carrizal ‘valley’ (with an annual rainfall of around 200 mm/a) was a horticultural area, but during the 1990s it was discovered to have exceptional soil and microclimate for export-quality viticulture and fruit production. As a result there have been major investments in irrigated agricultural development and the total cultivated area has now reached 12,000-14,000 ha, of which about 9,000 ha have pressurized systems and 1,500 ha are under drip irrigation.
- Much recent agricultural development has been based on the efficient, but intensive, utilization of groundwater resources and there are now 600-700 active production wells in the valley, giving rise to concerns about falling groundwater levels, competition amongst groundwater users, and between them and those dependent upon aquifer discharge in the Arroyo Carrizal. For this reason a ‘groundwater use restriction zone’ was declared in 1997, since estimated demand exceeded available resources in years of below average riverbed recharge.
- The juxtaposition of an equally-important petroleum industry in the valley, which dates back to the construction in 1943 of the YPF (now REPSOL) Luján de Cuyo Refinery at the northern head of the sub-catchment (Figure 3), has caused significant environmental hazards including concern about groundwater hydrocarbon pollution. The Ugarteche and Anchoris oilfields in the southern part of the valley (Figure 3) are also still in active production, and together with associated petrochemical industries, have further complicated the groundwater pollution hazard – especially in respect of saline oilfield formation water (Table 2) and also of hydrocarbon leaks and spillages. Groundwater quality concerns and protection needs now top the agenda of the regulatory agency.

Table 2: Chemical characteristics of ‘formation water’ from the Ugarteche oilfield

MAJOR DETERMINANTS		MINOR DETERMINANTS	
parameter	range (mg/l)	parameter	range (mg/l)
EC (uS/cm)	70,000 – 75,000	B (boron)	10
Cl (chloride)	19,000 – 26,000	Li (lithium)	5
Na (sodium)	2,000 – 16,000	Sr (strontium)	25 – 30
SO ₄ (sulphate)	900 – 1,100	As (arsenic)	0.04 – 0.08
K (potassium)	220 - 250	Cd (cadmium)	0.02 – 0.07
N (inorganic nitrogen)	5 - 25	Cr (chromium)	less than 0.01

Figure 4: Hydrogeological profile along the flow direction of the Carrizal aquifer system

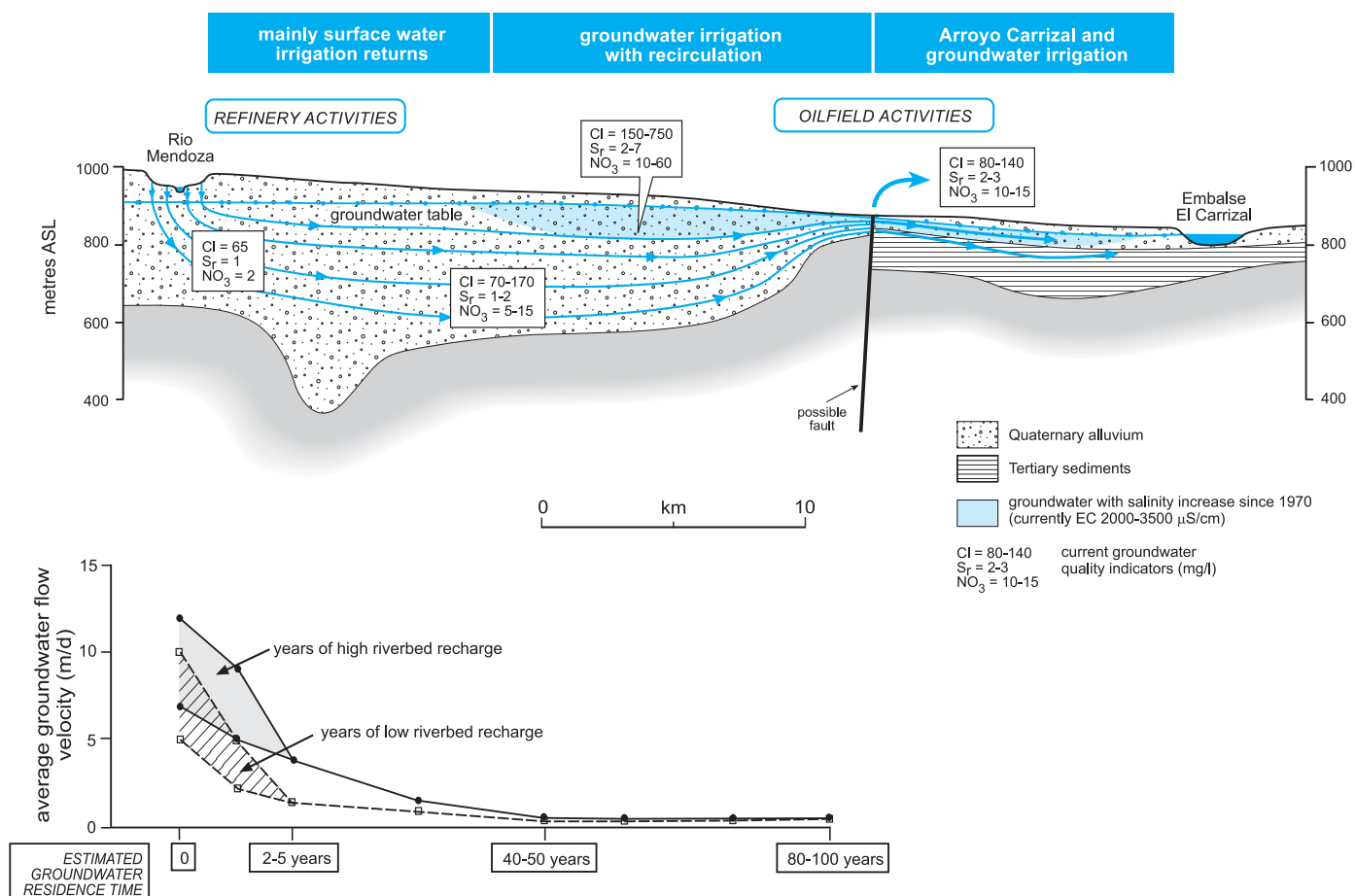


Figure 4 : Hydrogeological profile along the flow direction of the Carrizal aquifer system

Cooperative Investigation Programmes

- The DGI is attempting to resolve conflicts through a proactive groundwater management and protection program. The initial step is a series of cooperative agreements to improve scientific understanding of aquifer behavior. This 'partnership approach' (involving both public and private sector organizations) aims progressively to widen the base of stakeholder participation and foster shared appreciation of problems. It represents the most feasible option to mobilize adequate investment and cooperation to achieve effective management of groundwater resources and currently includes the following components:
 - **INA-CRA & CELAA:** Carrizal Aquifer Numerical Modelling as a base for Technical & Economic Analysis of Potential Water Resource Management Measures
 - **REPSOL-YPF:** Evaluation & Remediation of Hydrocarbon Pollution Risks at Luján de Cuyo Refinery
 - **MAYOP & INA-CRAS:** the Evaluation of Groundwater Salinity Problems.

Carrizal Aquifer Numerical Modelling

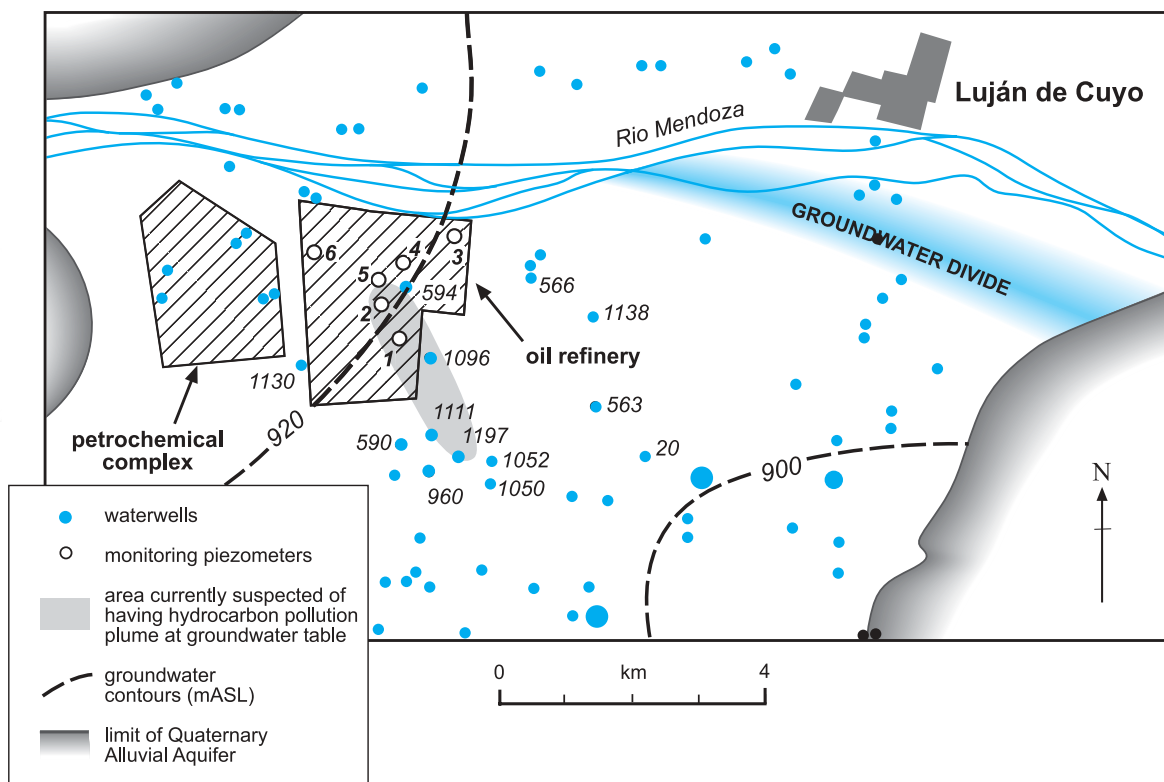
- The elaboration of the numerical aquifer model (using Modflow software) is a key tool for groundwater resource management – since it can provide a user-friendly basis for evaluation the groundwater flow regime, resource scenarios and management actions – and for communication with stakeholders.

- The development of the model necessitated significant fieldwork to improve existing databases on the hydrogeological structure and irrigation well abstraction/use patterns. But satisfactory model calibration with groundwater level data for 1979-99 (a period of relatively abundant surface runoff and riverbed recharge) has been achieved using reasonable values for aquifer parameters (K and Sy values up to maxima of 50 m/d and 0.20), although there remain uncertainties about the discharge to the Arroyo Carrizal and subsurface outflow to the Tununyan Valley.
- The implications of the model as currently calibrated are:
 - long-term equilibrium of the groundwater system but significant withdrawals from aquifer storage (up to 60 Mm³/a) to support abstraction in periods of below average riverflow
 - a groundwater divide between the Carrizal Aquifer and the Mendoza Northern Oasis whose position varies significantly (up to 3 km) in periods of below average recharge.
- The model has considerable potential for various applications from guiding resource management to assessing quality problems, including notably:
 - evaluation of management scenarios – such as (the possibility of) relaxing the ‘restriction area control’ and allowing an increase in abstraction or (the probable need) to impose more stringent controls and reduce abstraction to conserve groundwater quality
 - assessing impacts on the aquifer system of operation of the new Potrerillos dam, as a result of changes in the recharge regime in the Río Mendoza and its irrigation canals
 - preferred locations for the diversion of additional surface water into the area to substitute for groundwater abstraction and/or for direct aquifer recharge enhancement (which could be possible when Mendoza riverflow exceeds 80 m³/s)
 - the starting point for more detailed modelling to assess groundwater flow influencing potential contaminant transport in the vicinity of the REPSOL-YPF refinery complex
 - providing the physical basis for the modelling salt balance and groundwater salinity problems at aquifer level.
- However, the following aspects of the existing groundwater model require appraisal before it can be regarded as a robust management tool:
 - recharge from the Mendoza River estimated from riverflow by an empirical relation (based on incremental flow gauging in the early 1980s) whose validity may be open to question as a result of (a) riverbed deposition immediately upstream of the Cipoletti diversion structure in subsequent years, (b) radical changes in riverflow regime and clear water phenomena associated with construction and operation of the upstream Potrerillos Dam, which have to be taken into account from 2000 and predicted in the future
 - conditions of aquifer discharge, both subsurface via the southern boundary of the aquifer to the Tununyan Valley (current average outflow simulated as 45 Mm³/a) and the general regime of natural drainage to the Arroyo Carrizal (the watercourse itself not being easily gauged because of irrigation diversions).

Hydrocarbon Pollution Risks at Luján de Cuyo Refinery

- The Luján de Cuyo refinery is situated on the south bank of the Río Mendoza in the recharge area of the Carrizal Aquifer (Figure 5). It is underlain by a thick vadose zone (typically 100 m or more) but with large water-table fluctuations in years of abundant riverflow. Thus, despite the high-permeability piedmont alluvial deposits, aquifer pollution vulnerability is only moderate (with substantial pollutant attenuation capacity through capillary action, sorption, volatilization and biodegradation in the vadose zone). However, should this attenuation capacity be exceeded by heavy contaminant loading, extensive pollution plumes may develop as a result of the rapid groundwater flow rates (Figure 4) associated with high aquifer permeability and steep hydraulic gradient.

Figure 5: Sketch map of northern part of the Carrizal valley showing the Luján de Cuyo refinery



- Historically some waterwells in the general vicinity of the refinery have recorded apparent signs of hydrocarbon pollution and INA-CRAS work for YPF suggested that:
 - up to about 1995, 50-75 l/s of refinery effluent (probably containing high DOC, HC and salinity levels) infiltrated from 10 ha of unlined lagoons in the east of the refinery site
 - indirect indicators (EC, DO, COD, Eh) of a significant related groundwater pollution plume (probably containing hydrocarbons) were detected in 1993
 - an indication that this plume migrated at least 3 km SSE by 1996, but with numerous inconsistencies/limitations in the sampling approach and analytical data.
- The Luján de Cuyo refinery came under REPSOL management in 1998 (following the privatization of YPF in 1993) and they reached agreement with the DGI in 2002 on the installation of a network of groundwater quality monitoring piezometers within the refinery precinct to investigate and identify any potential groundwater pollution problems. The installation of this network was completed during 2003-04 (6 piezometers/of which 4 are of the most-favoured design). In November 2003, installation of piezometer no.1 (Figure 4) revealed significant hydrocarbon pollution at the deep water-table and this was later confirmed by piezometer no.2 (the following values being respectively recorded in April 2005 – THCs less than C7 = 19 & 97 mg/l, BTEX = 9 & 14 mg/l, MTBE = 12 & 27 mg/l). The source of this recent (and possibly active) pollution of ‘refinery final product’ appeared to be either in the oil-tanker loading area or the head pumping station of the main external pipeline (with MTBE being a useful persistent indicator of modern post-1995 processed hydrocarbon fuels).
- DGI has undertaken regulatory inspection of waterwells in the vicinity of the Luján de Cuyo refinery since 2000 – this has revealed that two wells (DGI no. 1096 & 1197) are experiencing pollution by a similar suite of contaminants, and four others (up to 2km from the refinery) have incipient contamination (Figure 4).

- In this situation M_{AY}OP and DGI were recommended to accept any reasonable short-term intervention proposed by REPSOL-YPF, without compromise to the longer-term strategy. Given the prevailing hydrogeological conditions, the initial action plan involved:
 - replacing the two seriously polluted waterwells with much deeper wells, carefully sealing off the uppermost 200 m of strata
 - assessing the contaminated land and environmental liabilities of the refinery site (using historic operational data and PETREX passive soil-gas sampling), and acting to remediate any current product leakage especially in the vicinity of piezometers no. 1 + 2
 - a ‘pump-and-treat’ approach in the vicinity of piezometer no.1, which should have the advantage of intercepting most of the outflow of hydrocarbons but could have the disadvantage of not necessarily removing them from the aquifer matrix.
- M_{AY}OP and DGI have agreed with REPSOL-YPF on the mobilization of an ‘independent international consultancy’ of 1-year duration (via the local university – UN de Cuyo) to develop a long-term action plan with attention to the following:
 - reviewing in detail the current groundwater pollution situation (including the effect of substantial groundwater level variations at the site), and assess whether the current groundwater pollution plume is growing, stable or contracting
 - undertake a risk assessment for the actual and potential groundwater pollution identified, and provide a concise risk management plan to eliminate on-going groundwater pollution
 - propose other priorities for strengthening and amplification of the groundwater piezometer sampling network
 - delineate control sub-areas with corresponding actions to mitigate the problem, including constraints on groundwater use and alternative water-supplies, monitored natural contaminant attenuation and, if necessary, more proactive contaminant removal.

Evaluation of Groundwater Salinity Problems

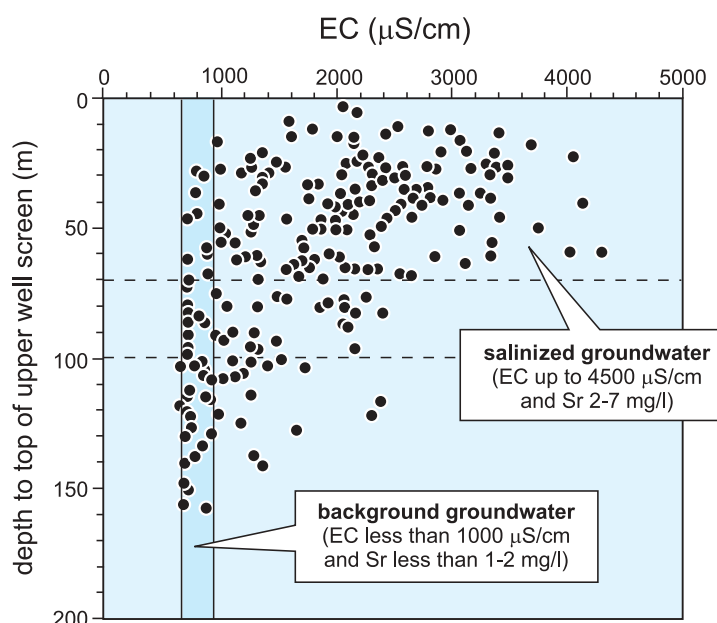
- This project had a number of interrelated objectives:
 - the 3-d field survey of groundwater salinity distribution in the southern part of the Carrizal Aquifer in the area sometimes referred to as Ugarteche-Anchoris
 - evaluation of the probable origin(s) of groundwater salinization (including leaching from desert soils during habilitation for irrigated cultivation, fractionation of salts from groundwater and agrochemicals by irrigated agriculture, infiltration of saline formation water from historic spillage or discharge during oil reservoir primary exploitation and/or secondary recovery, and lateral inflow and infiltration of ephemeral saline surface watercourses)
 - identify possible trace hydrocarbon pollution in parts of the area.

The results from the first stage of the investigation programme indicate:

- a clear overall stratification of groundwater salinity with significantly elevated EC (2,500-4,500 uS/cm) widely down to 70 m bgl and locally deeper, and with wells having deeper screen intakes mainly recording 1,000-2,500 uS/cm (Figure 6), compared to implied values of 1800 and 1000 uS/cm respectively for shallower and deeper groundwater during a preliminary UNDP reconnaissance in the late 1960s
- other major elements (such as Na, Cl, Ca, SO₄ and NO₃) and certain minor elements (Sr, Li) show a similar distribution

- the groundwater body with somewhat elevated salinity showed no trace of hydrocarbon contamination, and the very strongly oxidising groundwater conditions encountered throughout suggest that any minor contamination of the groundwater table with hydrocarbons was likely to have been rapidly degraded
- the Quaternary Aquifer is thinner and more patchily distributed in the southernmost part of this area than was originally anticipated, and most groundwater circulation occurs in the underlying highly-weathered Tertiary Mogotes Formation (which has a distinctive but not necessarily more saline hydro-chemical signature).

Figure 6: Correlation of groundwater salinity and well-screen depth in the southern part of Carrizal Aquifer (2003 data)



- The relatively uniform distribution of somewhat salinized groundwater suggests that the current regime of groundwater flow, irrigation use and return flow is a significant contributor to the problem. Its significance, and the possible contribution of oil-reservoir formation water and/or lateral naturally saline inflows, need to be further evaluated through:
 - extension of the area of hydrogeochemical survey northwards into the zone irrigated primarily with surface water
 - use of the existing numerical aquifer model to confirm the residence time of groundwater flow from the Mendoza riverbed (and surface water irrigation recharge) to aquifer discharge in the Arroyo Carrizal (Figure 4), and the level of implied re-circulation of groundwater and salts through irrigation use, given that irrigation is mainly restricted to the months of October-March
 - employ stable isotope analysis (2H and 18O) of samples from a hydrochemically- representative selection of waterwells to investigate further the origin of the observed groundwater salinity increases.
- There are also some indications of the presence in some shallower potable water-supply wells of certain toxic trace elements (mainly Cd and Cr) above national drinking-water standards, but these remain unconfirmed by initial comparative laboratory analytical trials in October 2004. Further work

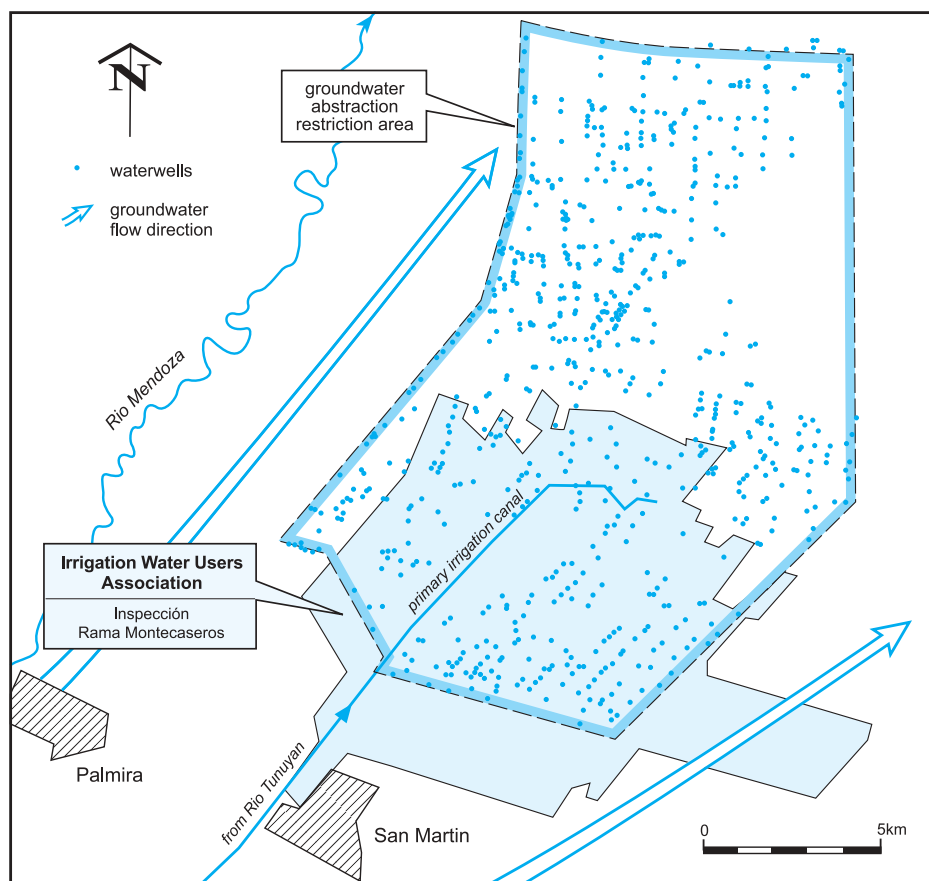
(including laboratory analytical quality controls, assessment of possible origins, evaluation of health risk, etc) needs to be carried out – and if the levels are verified an emergency water-supply plan must be developed and the possible impact on irrigated soils and crops assessed (although this is unlikely to be more significant than the salinity impact itself).

C: CONTROLLING GROUNDWATER SALINIZATION IN THE NORTHERN OASIS

General Hydrogeological Setting

- The Mendoza Northern Oasis is an extensive irrigation area with average rainfall of only 150-200 mm/a, but underlain by a major Quaternary aquifer system. The aquifer is mainly recharged from the Mendoza and Tunuyán rivers, directly as they emerge from adjacent hills onto highly-permeable alluvial fans and indirectly across extensive areas irrigated with surface water by seepage from canals and excess application at field level.
- With increasing distance from its upstream margin the aquifer system exhibits marked layering, with three aquifer units (separated by interbedded aquitards) widely recognised. Groundwater is abstracted to irrigate large areas outside the command of the main canals and elsewhere to supplement surface water at times of critical plant demand and in years of low riverflows.

Figure 7: Sketch map of the Montecaseros water-user association area and neighboring groundwater use restriction zone

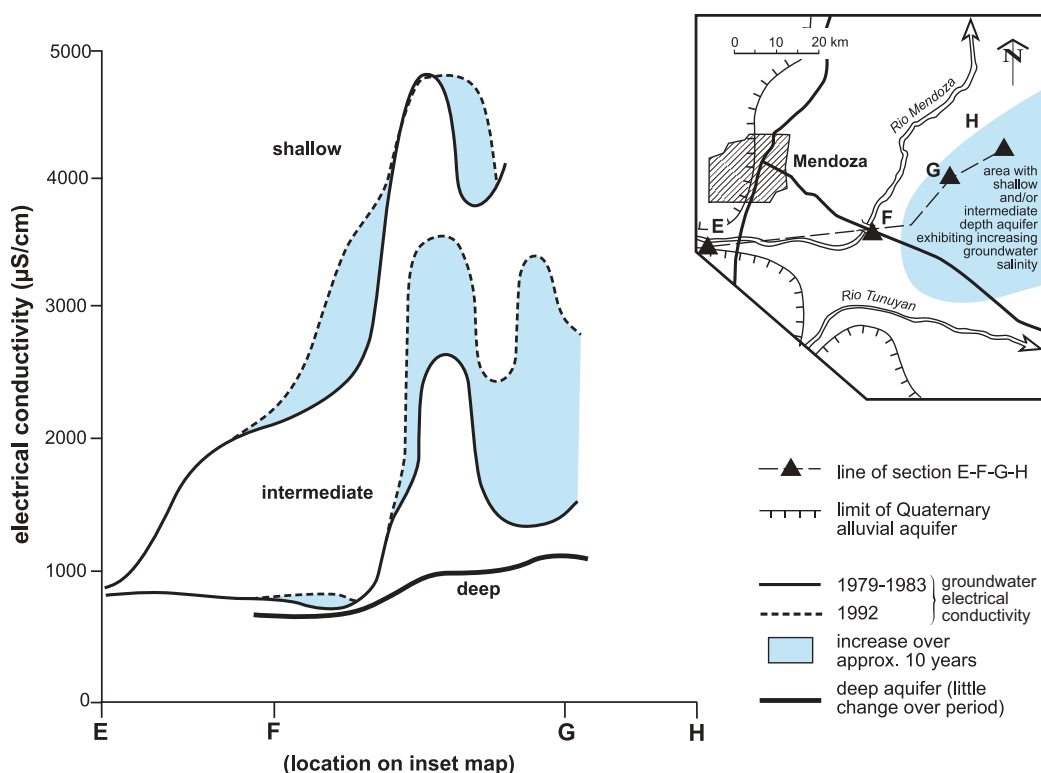


- The work described here focuses on the Montecaseros area of the Departamento San Martín, and is situated on the subdued interfluvium between the current courses of the Mendoza and Tunuyán rivers some 30 km from the alluvial fan recharge areas. A 'groundwater use restriction zone' of 23,180 ha extension (Figure 7) was declared here in 1995 as a result of an emerging problem of aquifer salinization.
- Groundwater salinity in the shallowest aquifer increased from 1000-1500 $\mu\text{S}/\text{cm}$ in the 1970s to 4500-5500 $\mu\text{S}/\text{cm}$ by 1995, and salinity increases had begun to penetrate to deeper aquifers (Figure 8). The total groundwater abstraction in the area is between 60-85 Mm^3/a , all of which is now drawn from the second and third aquifer levels.

Diagnosis of Groundwater Salinity Problem

- Increasing groundwater salinity was initially detected in the uppermost aquifer, mainly beneath well drained soils with water-table at 5-15 m depth. It appears to be the result of soil fractionation and concentration in irrigation return waters (rather than rising water-table and phreatic evapotranspiration), although there is also likely to be an important component through mobilization of salts from the vadose zone, when the soils were first brought under irrigation.
- Over recent decades farmers have constructed increasingly deeper wells to tap groundwater in the semi-confined aquifers which exhibited excellent quality. However, heavy pumping from these deeper aquifers, led to widespread reversal of the natural vertical hydraulic gradient and salinity being drawdown into the second aquifer (Figure 8), threatening its use for irrigation of high-value, salt-sensitive, crops and causing serious impacts in an area with excellent micro-climate for export-quality viticulture and fruit trees.

Figure 8: Evolution of groundwater salinity in the Quaternary multi-aquifer system of the Mendoza northern oasis

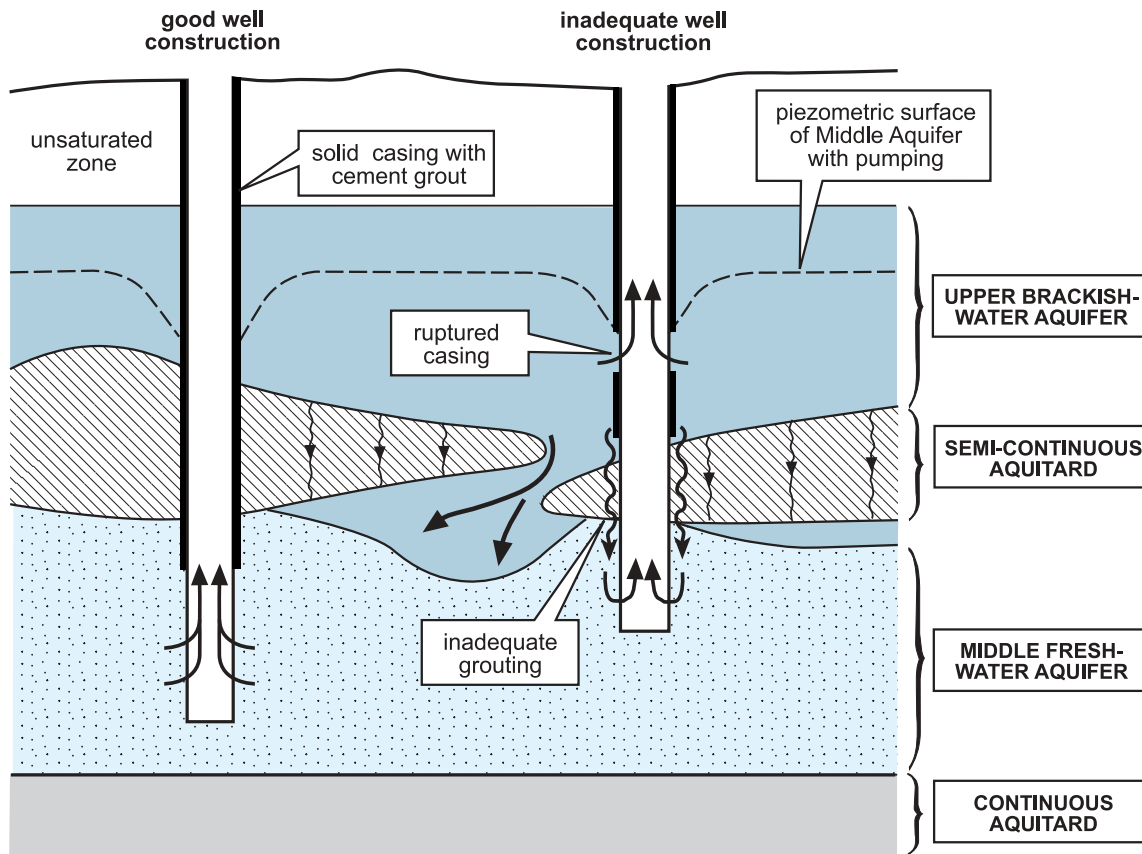


- The cause of the induced downward migration of saline groundwater is being further assessed but appears to be related to:
 - low natural hydraulic gradients (below 0.005) and thus small groundwater throughflows in the semi-confined aquifers
 - the fact that downward vertical leakage is more readily induced by pumping than increased horizontal groundwater flow.

It is tentatively concluded that 70% or more of the supply pumped from the second aquifer level is derived from the overlying strata.

- The existence of substantial numbers of poorly-constructed and/or highly-corroded wells, many of which have been abandoned, is further aggravating the groundwater salinization problem by providing conduits for downward migration of brackish water from the phreatic aquifer (Figure 9). The relative significance of this process is also being systematically evaluated by short-term pumping tests from representative waterwells with continuous salinity monitoring. Initial indications are that overall this process is of minor significance volumetrically, compared to induced vertical leakage, and affects most seriously the actual owner or user of the corroded well itself and the immediate neighbours.

Figure 9: Mechanisms contributing to the downward migration of saline groundwater in a multi-aquifer sequence



Strategy for Groundwater Salinity Control

The following are the main components of the strategy to control aquifer salinization:

- substantially reduce pumping of groundwater from deeper aquifers to reduce the rate of downward leakage, by transferring 'additional surface water' into the area (Figure 7) with irrigators relinquishing groundwater abstraction rights (concessions)
- improve the efficiency of surface-water irrigation and effect real water savings, by lining secondary/tertiary canals and introducing pressurised irrigation systems at field level, so as to make water available for transfer and reduce infiltration to the uppermost saline aquifer thus avoiding water-table rise and/or increase in the downward hydraulic gradient
- a complementary action will be to backfill and seal numerous poorly-constructed wells acting as a 'short cut' for the downward migration of shallow saline groundwater.

A combination of these actions is capable of bringing about the alleviation of the groundwater salinity problem in the short to medium-term. However, a long-term fully sustainable solution will require the drainage of saline water from the phreatic aquifer, if economically feasible.

Publication Arrangements

The GW•MATE Case Profile Collection is published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

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