

Sustainable Groundwater Management Lessons from Practice

Case Profile Collection Number 6*

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

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(*revised from November 2002 and June 2005 versions)

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This case profile relates to advice provided to the DGI¹-Mendoza 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 MAyOP¹. In two important areas of the principal Mendoza oasis, salinization processes are threatening the naturally high-quality of groundwater and causing serious concern about impacts on sensitive commercial vineyards and fruit orchards. More locally oil field 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, INA¹ – CRA¹, CELAA¹ & CRAS¹ offices – with GW-MATE being mobilized under the general umbrella of the World Bank/Inter-American Development Bank PROSAP¹ (DGI-Mendoza ‘Calidad de Agua y Suelo’ Component) and also via GWP-SAMTAC¹.

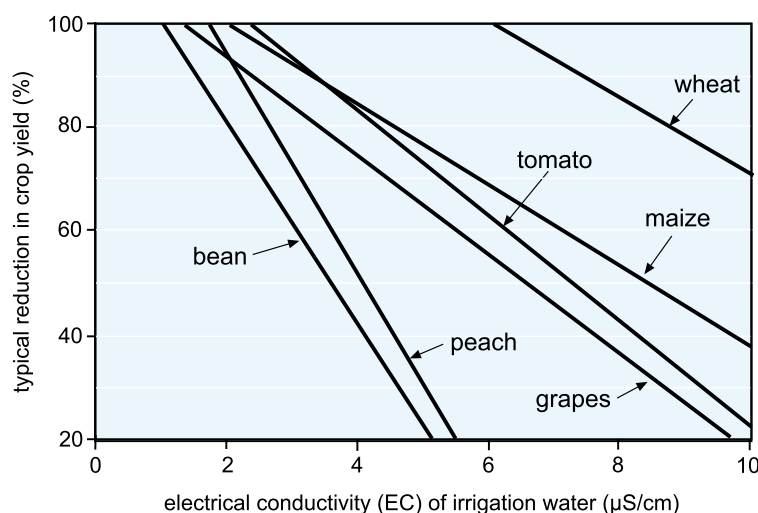
A: REVIEW OF GENERAL APPROACHES TO GROUNDWATER MANAGEMENT

- The DGI is an autonomous water resource authority, which maintains good hydrological records and agricultural water-use data. It takes a proactive approach to water provision for irrigated agriculture and urban water-supply, and is attempting to integrate groundwater more consistently into the provincial hydraulic infrastructure and water resource plan, which has a long history as regards surface water development and administration. Although the DGI is charged with responsibility of controlling and policing polluting discharges to water, more general powers to control land use and polluting emissions rest with MAyOP.
- The initial DGI 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 encountered problems in 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 in the salinity-sensitive vineyards and orchards (Figure 1) of high value and export quality.

¹ DGI—Irrigation Department; MAyOP—Ministry of Environment and Public Works; INA—National Water Institute; CRA—Regional Water Center; CELAA—Water Economy, Legislation and Administration Center; CRAS—Regional Groundwater Center; PROSAP—Provincial Agricultural Services Program; GWP-SAMTAC—Global Water Partnership-South American Technical Group

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



- 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, as a basis for knowing the water users, understanding the incentives to which they respond, and thus facilitating their greater involvement in resource management.
- The socio-economic profile of water resource use in Mendoza is relatively unusual in that :
 - groundwater users include a high percentage of recently-established major international wine producers using modern high-efficiency irrigation methods
 - amongst surface water users, long-standing smallholders using traditional low-efficiency irrigation techniques still dominate, although practices are changing.
 The reallocation of water resources from latter to former in the interests of aquifer management tends to encounter opposition on grounds of 'property rights' and generate social friction.
- In addition to the major international wine companies and the smaller local wine and fruit producers, the stakeholders in groundwater use also include other agricultural irrigators (eg. for vegetable production), public water-supply services and (in some areas) petrochemical and other industrial abstractors.

Groundwater Use Restriction Zones

- The strategy of introducing 'groundwater use restriction zones' in areas of increasing salinity must 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 (despite the fact that trading of water rights is not permitted by provincial water law).

This ‘replacement well clause’ is however capable of abuse by drilling the substitute water well distant from the original well, which is then only temporarily capped and subsequently brought back into production.

- Unfortunately groundwater abstraction rights have always been granted ‘in perpetuity’ and thus ‘clawback’ is not generally possible at the time of mobilizing finance for irrigation modernisation to pressurised systems (with drip and micro-spray application) – and this may lead to a tendency to use the ‘saved water’ to extend the irrigated area. However, 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 permitted (with DGI as intermediary), but with the local cost of irrigation modernisation running from 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 (‘canon’) 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 legitimately 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.
- 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 and pump installation.

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



Water-User Participation in Resource Management

- Water-user associations (WUAs), known locally as ICs ('Inspecciones de Cauce') and based on the primary irrigation canal infrastructure, have existed successfully 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;

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/yr/well	not applicable
Water Resource Fee		US\$ 10-15/yr/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

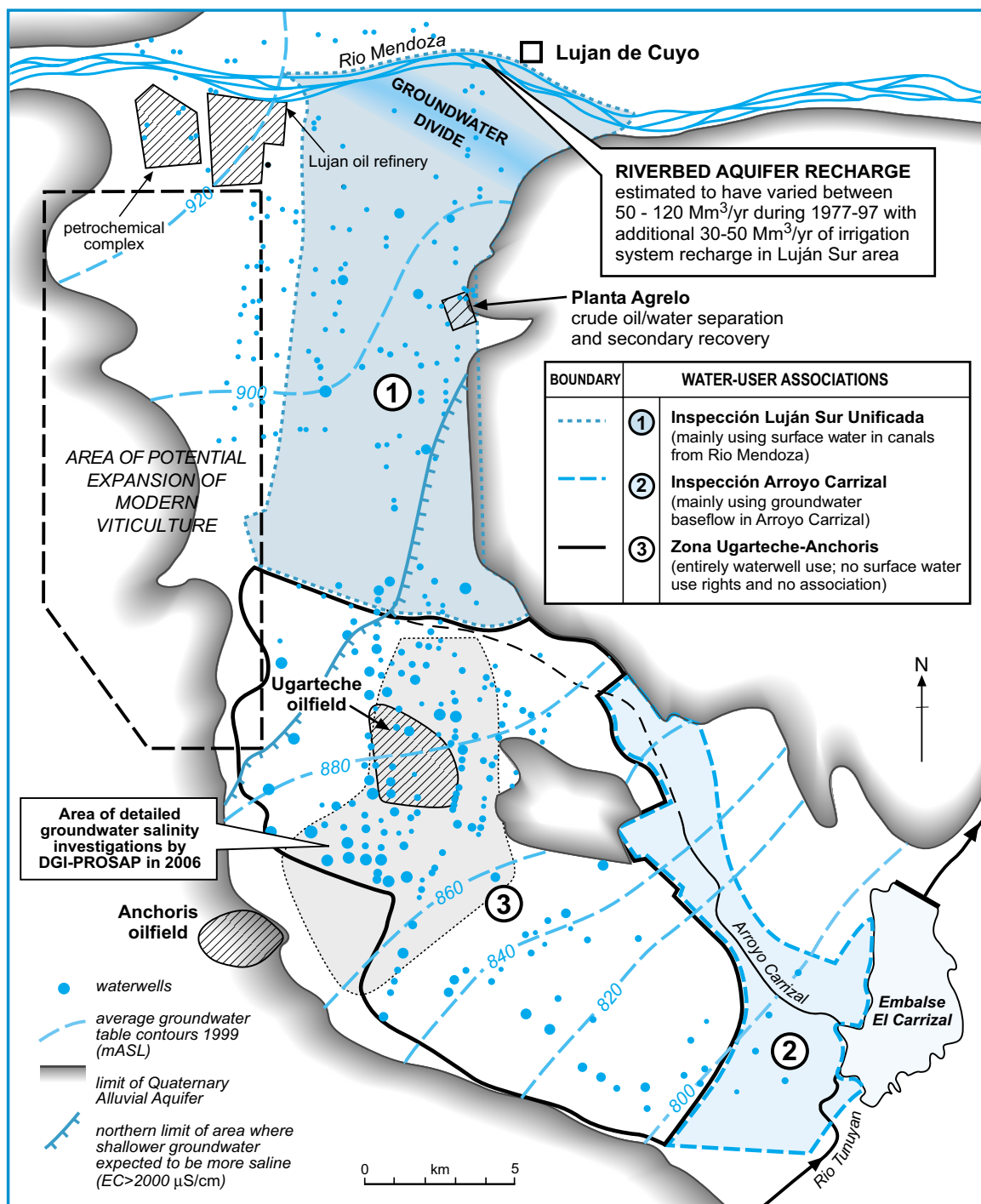
- historically the WUAs are organized around primary irrigation canals and neither their territorial scale nor their boundaries are really suitable for aquifer management
- there is reluctance by groundwater-only irrigators outside present WUA boundaries to join and contribute to the neighboring WUA, 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 may thus eventually be to promote formation of an aquifer management organizations (AMORs) for critical 'groundwater bodies', involving the groundwater users (preferably grouped into a new WUA), representatives of the existing WUAs, the public water-service company and other major 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 quality degradation.
- 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 remains difficult for DGI to promote community participation in groundwater management until 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-Lujan 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 flow path beyond to the Tununyan river is partly in highly-weathered Tertiary (Mogotes) Formation.
- In the 'natural condition' groundwater recharge originated as infiltration over a 10 km stretch of the bed of the Rio Mendoza and aquifer discharge created the Arroyo Carrizal (a tributary of the Rio Tununyan). The rate of riverbed recharge (determined by differential gauging) varied considerably with river flow regime, but it is estimated to have averaged 85 Mm³/yr during 1979-94, with a further 40 Mm³/yr or so of river-water diverted for irrigation in the Lujan Sur area taken to end-up as groundwater recharge.
- A new dimension for groundwater resource management in the area relates to the 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 river flow regime began gradually from 2000 but the full

Figure 3 : Sketch map of the Carrizal aquifer system



effects of diversion have only begun to be felt in the last 1-2 years – they will reduce 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 some 200 mm/yr) was a horticultural area, but during the 1990s it was discovered to have exceptional soil and micro climate for export-quality viticulture and fruit production. As a result there have been major investments in modern irrigated agricultural development (with pressurised ferti-irrigation systems, vines under anti-hail nets, minimal tillage using glyphosate herbicides and copper fungicides).
- There is need to re-assess the rate of expansion of the total cultivated and irrigated area but it has probably now passed 14,000 ha. Of this about 9,000 ha have pressurised systems, 1,500 ha are under drip irrigation and a further 7,800 ha are due to receive 'clear surface water' from a new pressurised irrigation pipeline – the change will have the indirect effect of reducing aquifer recharge through flow reduction in the main irrigation canals of the Inspeccion Lujan Sur.
- Today agricultural land prices on the western flanks of this broad valley are the highest of anywhere in Argentina (from US \$ 30-50,000/ha for land with productive vines and water use rights to US\$ 4,000/ha for barren land). This is putting tremendous pressure on groundwater resources, since most of the recent agricultural development has been based on the efficient, but intensive, utilisation of groundwater and there are now 600-700 active production wells in the valley. Moreover, monitoring of rural electrical energy consumption in the area during 2006 has revealed consistently elevated 'use factors', reflecting the very high dependence on these water wells for agricultural irrigation.
- This general trend started to give rise to concern some years ago about falling groundwater levels, increasing groundwater salinity in some areas, 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 – and this zone is under greater pressure than ever today. A qualitative indication of the effect of various land and water management measures on the aquifer groundwater balance is given in Table 2.

Table 2 : Effect of land and water management activities on the Carrizal Aquifer water balance

ACTIVITY or MEASURE	EFFECT ON BALANCE	COMMENTS
<i>deliver surface water by lined canals/ pipelines</i>	- -	tends to eliminate groundwater recharge from return flows and increase consumptive use
<i>introduction of drip irrigation techniques</i>	- -	
<i>backfill or effectively seal all disused waterwells</i>	+	prevents subsequent re-commissioning
<i>reduce rural electrical energy subsidy</i>	+	but only impacts smaller irrigators
<i>police and reduce illegal pumping (duplicate waterwells, oversized pumps)</i>	++	requires increased field inspections and realistic sanctions
<i>Increase riverbed recharge (clear water, bed modification)</i>	++	difficult to predict response and its temporal variation
<i>provide canal water to groundwater only areas</i>	++	allows reduced groundwater use in critical areas

- The juxtaposition of an equally-important petroleum industry in the valley, which dates back to the construction in 1943 of the YPF (now REPSOL) Lujan 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 oil fields 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 oil field formation water (Table 3) and also of hydrocarbon leaks and spillages. Groundwater quality concerns and protection needs now top the agenda of the regulatory agency.

Table 3 : Chemical characteristics of ‘formation water’ from the Ugarteche oil field

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

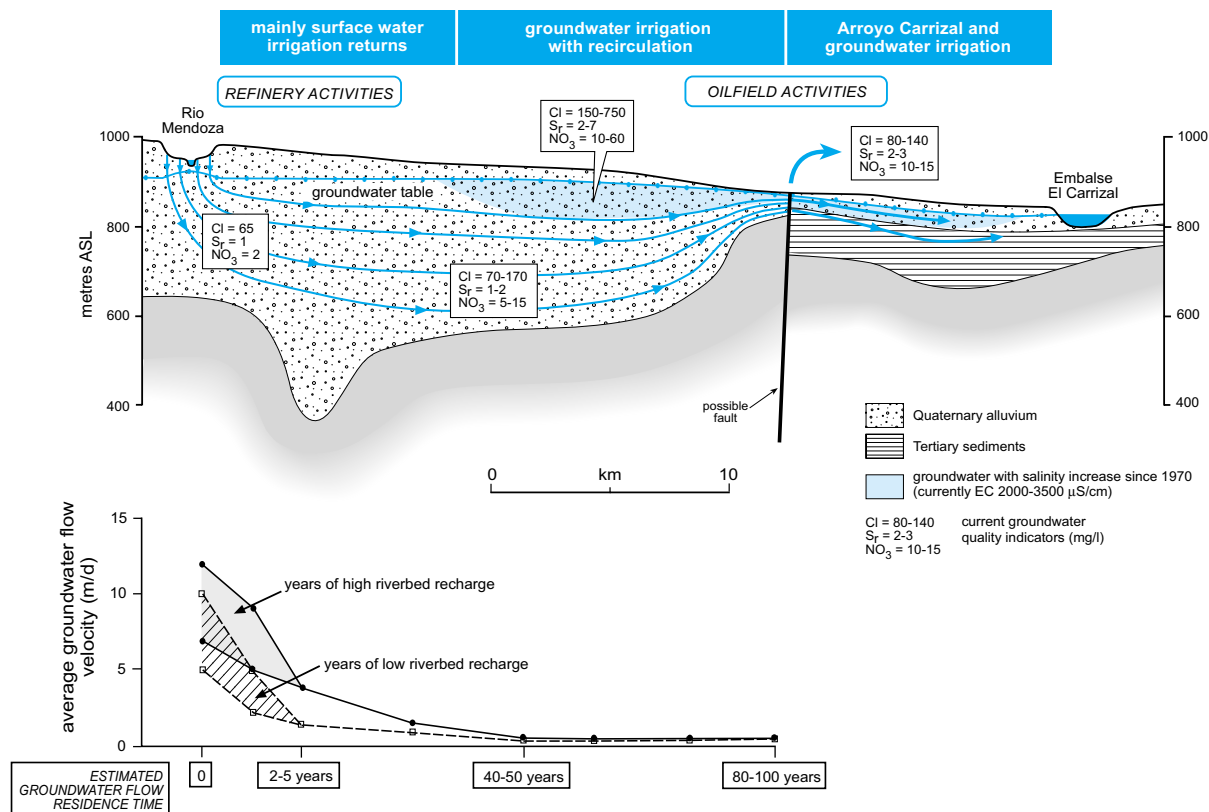
Cooperative Investigation Programmes

- The DGI is attempting to resolve the emerging conflicts through a proactive groundwater management and protection programme. 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 mobilise adequate investment and cooperation to achieve effective management of groundwater resources and has included 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 Lujan de Cuyo Refinery
 - MArOP & 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 of 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. Recharge from the Mendoza River was estimated from river flow by an empirical relation (based on incremental flow gauging in the early 1980s). But satisfactory model calibration with groundwater level data for 1979-99 (a period

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



of relatively abundant surface runoff and riverbed recharge) has been achieved using reasonable values for aquifer parameters (K and S_y values up to maxima of 50 m/d and 0.20), although there remain uncertainties about the discharge to the Arroyo Carrizal (the watercourse itself not being easily gauged because of irrigation diversions) and subsurface outflow to the Tununyan Valley (current average outflow simulated as 45 Mm^3/yr).

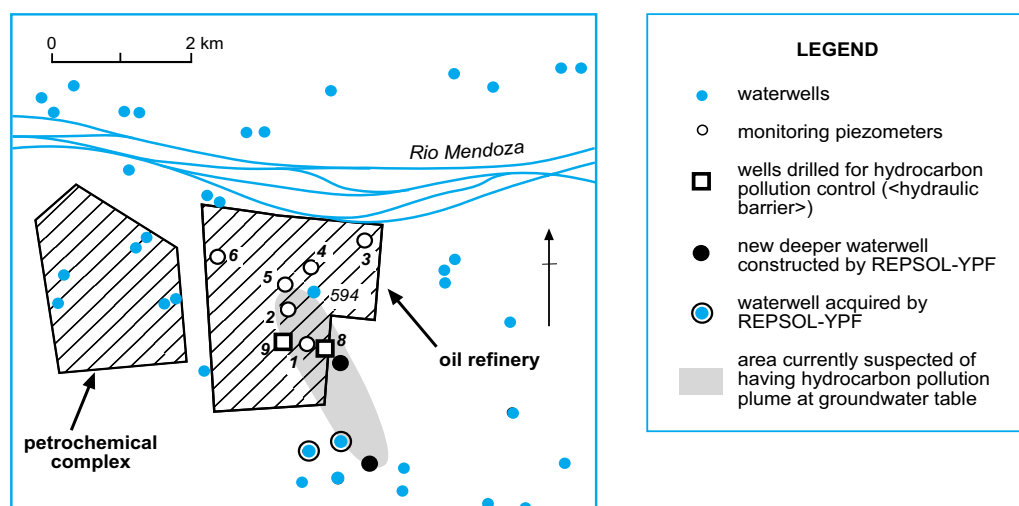
- The implications of the model as currently calibrated are :
 - long-term equilibrium of the groundwater system but significant withdrawals from aquifer storage (up to 60 Mm^3/yr) to support abstraction in periods of below average river flow
 - a groundwater divide between the Carrizal Aquifer and the Mendoza Northern Oasis whose position varies significantly (up to 3 km) in periods of below average recharge.
- The priority now is to use the numerical model (re-calibrating as necessary) to assess the impact on the aquifer system of operation of the new Potrerillos dam during 2000-06 (in effect the progressive change in river flow regime and the increasing presence of 'clear water') – first indications are of increased recharge rates overall, reflected by major increases (10-25 m) in groundwater level by February 2006, but this needs to be investigated systematically.
- The model should then have considerable potential for evaluating the impact of changes in surface water utilisation and administration, for guiding groundwater resource management decisions and for assessing groundwater quality problems including :
 - 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
- 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 river flow 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.

Hydrocarbon Pollution Risks at Lujan de Cuyo Refinery

- The Lujan de Cuyo refinery is situated on the south bank of the Rio 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 river flow. Thus, despite the high-permeability (piedemonte) 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 Lujan de Cuyo refinery



- Historically some water wells 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.

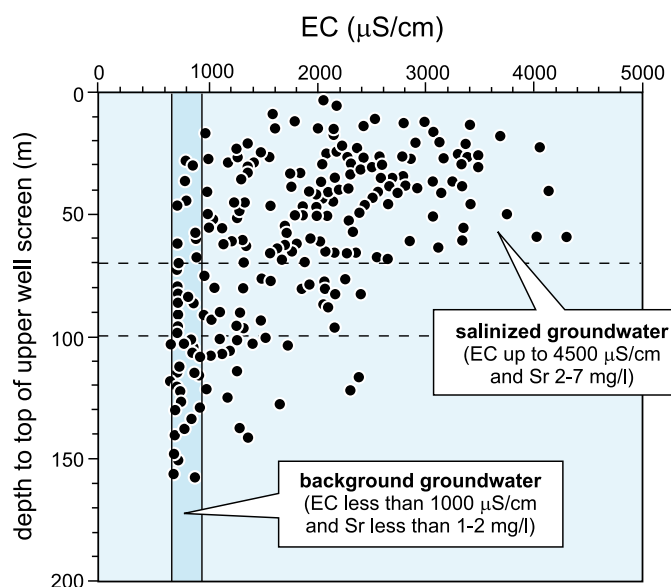
- The Lujan de Cuyo refinery came under REPSOL management in 1998 (following the privatization of YPF in 1993) and they reached a partnership agreement with the DGI in 2002 on the installation of a network of groundwater quality monitoring piezometers within the refinery precinct to investigate and identify 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 during 2006 : BTEX = 8-28 & 12-36 mg/l, MTBE = 3-24 & 9-13 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 water wells in the vicinity of the Lujan 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 MAYOP 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 water wells with much deeper wells, carefully sealing off the uppermost 200m of strata (Figure 4)
 - 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 and 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.

It is noteworthy that the estimated overall total capital cost of the groundwater pollution evaluation, control and mitigation measures already implemented by REPSOL is probably in excess of US\$ 4.0 million, excluding a much larger investment in refinery modernisation to reduce the risk of future serious groundwater pollution incidents.
- MayOP and DGI have also agreed with REPSOL-YPF on the mobilisation of an 'independent international consultancy' of about 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

- The investigation programme 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 most significant features of the results to date are :
 - a clear overall stratification of groundwater salinity with significantly elevated EC (2,500-4,500 $\mu\text{S/cm}$) widely down to 70 m bgl, and with wells having deeper screen intakes mainly recording 1,000-2,500 $\mu\text{S/cm}$ (Figure 6), compared to implied values of 1800 and 1000 $\mu\text{S/cm}$ respectively for shallower and deeper groundwater during a preliminary UNDP reconnaissance in the late 1960s
 - other major elements (such as Na, Cl, Ca, SO_4) and certain minor elements (Sr, Li, NO_3) show a similar distribution
 - the groundwater body with somewhat elevated salinity showed no trace of hydrocarbon contamination, and the very strongly oxidizing groundwater conditions encountered throughout suggest that any minor contamination of the groundwater table with hydrocarbons was likely to have been rapidly degraded.
- The relatively uniform stratified distribution of salinized groundwater has been confirmed by a more detailed investigation by DGI-PROSAP during 2006 in the area of the Ugarteche-Anchoris oil field (Table 4), which also recorded similar results for Sr and Li, and a complete absence of dissolved hydrocarbons and other indicators of oil field formation water.

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



- The observed distribution of salinity during 2003-04 suggests that the current regime of groundwater flow, irrigation use and return flow is a significant contributor to the problem – but other factors such as leaching from desert soils during habilitation for irrigated cultivation, lateral naturally saline inflows and the presence of localized ‘hotspots’ affected by oil field formation water need to further evaluated. There is clearly need to :
 - extend the area of hydrogeochemical survey northwards into the zone irrigated primarily with surface water
 - use the numerical aquifer model to confirm residence times 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)
 - undertake stable isotope analysis (2H and 18O) of samples from a hydrochemically-representative selection of water wells to investigate further the origin of the observed groundwater salinity.

Table 4 : Chemical characteristics of Carrizal Aquifer groundwater in the Ugarteche-Anchoris oil field from DGI-PROSAP investigation of 2006

AQUIFER DEPTH	ANALYTICAL RESULTS	DETERMINAND (in mg/l except as indicated)				
		EC (μS/cm)	Cl	Na	SO ₄	Ca
UPPER LEVELS	maximum	4100	610	413	1663	674
	average	2690	347	199	956	382
LOWER LEVELS	average	1330	120	126	444	135
	minimum	660	52	65	217	63

- There were also some indications in 2003-04 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 were not confirmed by follow-up comparative laboratory analytical work in 2004 nor by the detailed DGI-PROSAP investigation of 2006.

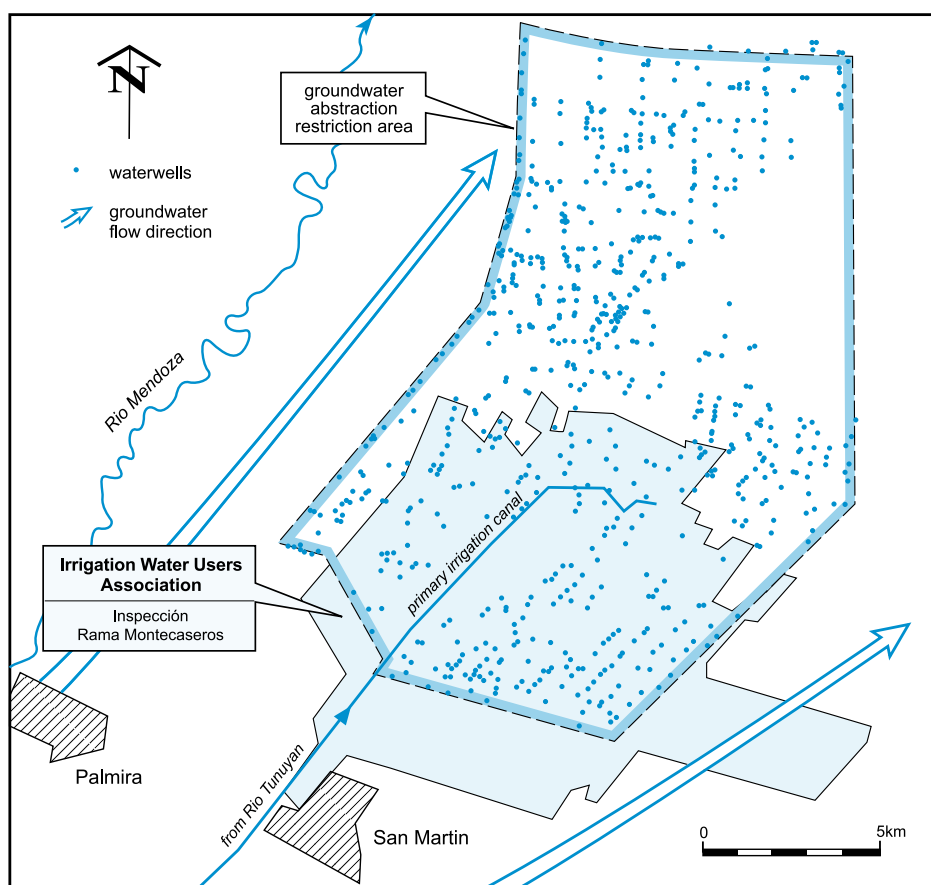
C : CONTROLLING GROUNDWATER SALINIZATION IN THE NORTHERN OASIS

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 Tunuyan 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 sub-aquifer units (separated by interbedded aquitards) being widely recognized. Groundwater is abstracted to irrigate large areas outside the command of the main canals and also to supplement surface water at times of critical plant demand and in years of low river flows.

- 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 (Figure 7). A 'groundwater use restriction zone' of 23,180 ha extension was declared here in 1995 as a result of an emerging problem of aquifer salinization.

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



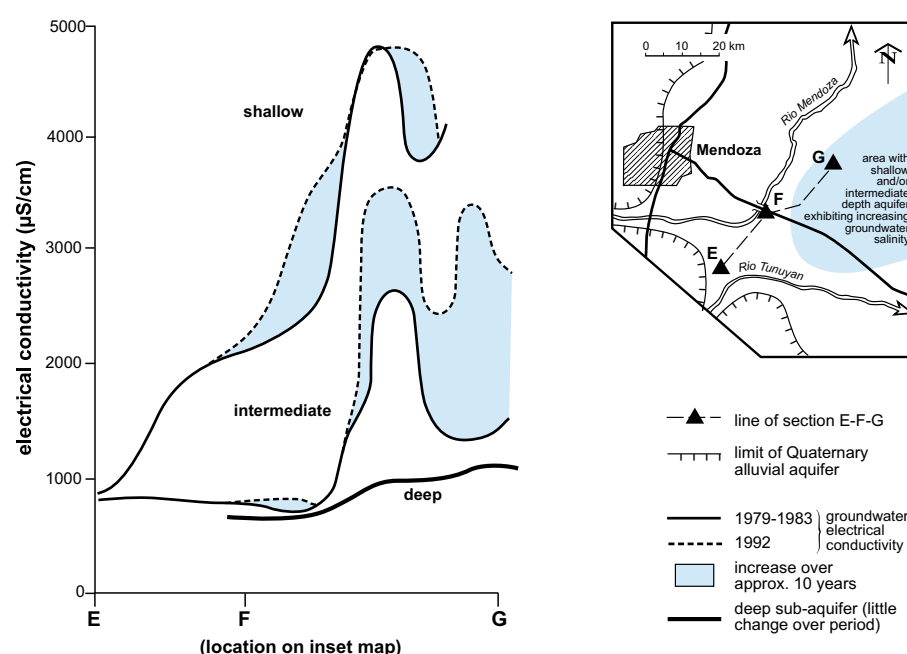
- Groundwater salinity in the shallowest sub-aquifer increased from 1000-1500 uS/cm in the 1970s to 4500-5500 uS/cm by 1995, and salinity increases had begun to penetrate to deeper sub-aquifers (Figure 8). The total groundwater abstraction in the area is between 60-85 Mm³/yr, all of which is now drawn from the second and third sub-aquifers.

Diagnosis of Groundwater Salinity Problem

- Increasing groundwater salinity was initially detected in the uppermost sub-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), but there is also likely to be an important component of salt mobilisation from the vadose zone when soils were first brought under irrigation.

- Over recent decades farmers have constructed increasingly deeper wells to tap groundwater in the semi-confined sub-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 drawn into the second sub-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 viniculture and fruit trees.

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



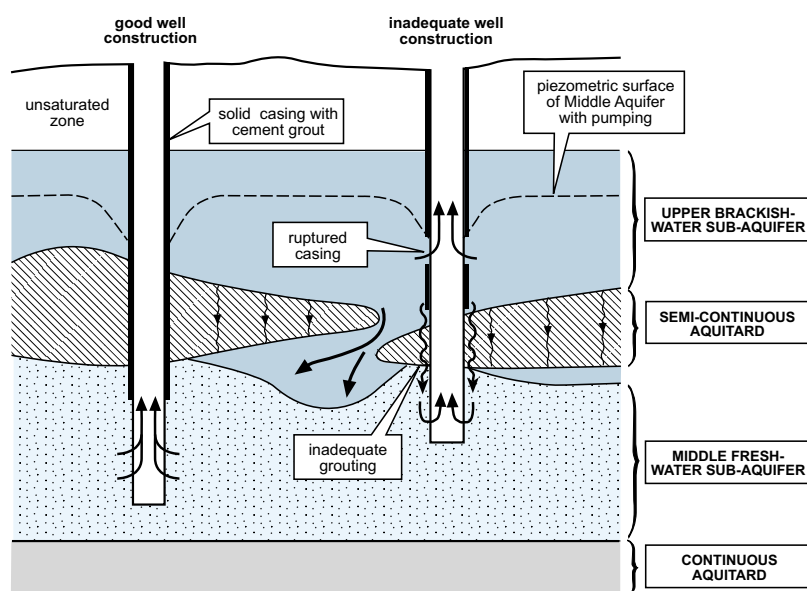
The cause of the induced downward migration of saline groundwater is being further assessed but appears to be related to :

- low natural hydraulic gradients (below 0.005) and thus small groundwater through flows in the semi-confined sub-aquifers
- the fact that downward vertical leakage is more readily induced by pumping than increased horizontal groundwater flow.

And it is tentatively concluded that 70% or more of the supply pumped from the second sub-aquifer is derived from 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 water wells 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 neighbors.

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



Strategy for Groundwater Salinity Control

- The following strategy has been recommended to control aquifer salinization :
 - substantially reduce pumping of groundwater from deeper sub-aquifers to reduce the rate of downward leakage, by transferring 'additional surface water' into the area (Figure 7) with irrigators being persuaded to relinquish 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
 - seal and backfill 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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