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## 8

# Conjunctive Management of Surface Water and Groundwater in the Middle Río Lerma Basin, Mexico

### Christopher A. Scott and Carlos Garcés-Restrepo

In Mexico and around the world, a great deal of emphasis is currently placed on 'water savings' through more efficient use of irrigation water. The underlying assumption is that water applied in excess of crop demand is 'lost', presumably as drainage outflow from the system or evaporation of water pounded within the system. Following this line of reasoning, applying irrigation water more sparingly would result in some combination of the following three outcomes:

- increase in reservoir storage carryover for the next irrigation season;
- increase in the area irrigated under present cropping patterns; and
- intensification of irrigation leading to higher-water-demand crops (higher-value crops) planted on the present irrigated area.

In order to achieve such outcomes, major rehabilitation and modernization programmes are implemented in which canals are lined and efficient water application technologies (drip and sprinkler) supplant traditional flood or furrow irrigation. The question is whether these measures would achieve real water savings.

The International Water Management Institute (IWMI) has questioned the classical conception of irrigation efficiency, particularly in the context of river basins where water is reused (Seckler 1996; Molden 1997). The unforeseen outcome of conventional initiatives to rehabilitate or modernize irrigation infrastructure may simply be to reduce a third party's water supply. These are referred to as 'dry water savings' as distinct from 'wet water savings', which do not produce such reductions. In river basins where surface and groundwater resources are coupled—this is the case in most basins—'low efficiency', or 'leaky' surface irrigation systems play an important aquifer recharge function. This chapter explores the implications of conjunctive surface and groundwater management for the middle Río Lerma basin in Mexico and shows that reducing surface supplies (e.g. 'saving water') may have profound and negative effects on the basin's aquifers.

In the following analysis, we operationalize the IWMI river basin water-accounting framework (Molden 1997). Water inflows to the basin are categorized as gross inflows from precipitation and runoff, plus (or minus) any change in storage. Outflows include committed (existing downstream water rights) and uncommitted flows (losses to the sea), whereas depletions are crop evapotranspiration (ET) and evaporation from the soil and pounded water. Where no utilizable outflow occurs in the dry season, the basin is said to be 'closed'. This is the case for both the middle Lerma and the Lerma–Chapala basins, for which analysis are presented below.

## CONCEPTUAL APPROACH

The concept of relative water supply (RWS) was originally introduced by Levine in the mid-seventies and fully discussed later (Levine 1982). It is used widely as an irrigation-system diagnostic tool that not only describes the hydraulic performance of the system, but also sheds light on the causes of that performance. Thus, the variable constitutes a powerful analytical tool as it incorporates the 'management' element and farmer reaction to perceived water availability. It is defined as:

$$\text{Relative Water Supply} = \frac{\text{Total Water Supply (Irrigation + Precipitation)}}{\text{Total Crop Demand}}$$

where the denominator includes consumptive use and non-beneficial ET. In the original definition, precipitation is taken to be total (Levine 1982).

RWS can be evaluated essentially at any location where the water supply can be measured or estimated, and the demand determined: on-farm, turnout, lateral, system or basin level. Given the nature and flexibility of this indicator, its use and definition are often adapted to the particular situation at hand. Most of the modifications deal with the definition of the numerator, that is, total water supply (TWS). A frequent change deals with the handling of rainfall—total or effective—and how surface water availability is treated. The reader should be aware that the groundwater contribution, as through capillary rise, is not included. There is no conceptual limitation, however, to evaluating RWS for groundwater irrigation where TWS includes the volumes pumped.

In this chapter, the relative water supply concept is applied in the context of a river basin ($\text{RWS}_{\text{basin}}$, or $\text{RWS}_b$); therefore, total surface water supply ($\text{TWS}_s$) is defined in the following manner to better reflect surface water availability:

$$\text{TWS}_S = P + (Q_{ri} + Q_{si}) - (Q_{ro} + Q_{so})$$

where:

P is precipitation (effective, using the US Bureau of Reclamation method of $0.8{*}P_{\text{total}}$)

$Q_{ri}$ is river inflow

$Q_{si}$ is surface irrigation inflow (reservoir release)

$Q_{ro}$ is river outflow

$Q_{so}$ is surface irrigation outflow (downstream release to irrigated area outside the system)

Reservoir release $Q_{ri}$ will be used below as a management variable. Outflows include both committed and uncommitted components, with emphasis on the latter. This change will yield, in general, lower values of $\text{RWS}_b$ than those defined by Levine (here denoted $\text{RWS}_{\text{irrigation}}$ or $\text{RWS}_i$, which do not consider outflows utilized downstream in the basin). Given that peak river outflows are not readily utilizable for crop production, in our opinion our definition of $\text{RWS}_b$ better reflects the true nature of the supply/demand relationship in river basins.

## STUDY AREA

The basin of the Lerma-Santiago river system drains much of the highlands of west-central Mexico and empties into the Pacific Ocean. The basin comprises a number of sub-basins, most importantly the Lerma river (Río Lerma) which flows into Lake Chapala (when lake levels are sufficiently high, the outflow is called Río Santiago). The Lerma–Chapala basin, which covers some 54,000 km², is undergoing rapid economic and social change. A dynamic agricultural sector and a rapidly growing industrial sector, which accounts for 35 per cent of Mexico's industrial GNP, characterize the basin. The first of Mexico's river basin councils has been established in the basin, and will likely be a model for others to follow. The council has passed binding regulations on upstream surface water withdrawals in order to control the rapid decline in surface water availability and quality in the lower basin.

While the mean annual runoff in the Lerma–Chapala basin represents a little over one per cent of Mexico's total runoff, the basin

contains over 10 per cent of the population and 14 per cent of the irrigated area in the country. Hence, the basin is faced with growing water shortages, with current average annual water availability per capita at around 950 m³. Since at least the mid-eighties, water resources in the basin have been overcommitted, resulting in significant pressure on surface water sources and alarming declines in the levels of groundwater and Lake Chapala (De Anda *et al.* 1998). Moreover, water quality is a rapidly increasing problem. Most significantly, water is being reallocated from the agricultural to the urban and industrial sectors, albeit in an uncoordinated manner. With over 700,000 ha of irrigation in the Lerma–Chapala basin, the study area is important from the perspective of agricultural production. Irrigation consumes approximately 78 per cent of the water resources in the basin (Mestre 1997).

The middle Lerma basin, for purposes of the analysis presented in this essay, is defined as the river reach below the Solís Dam to the Markazuza Diversion (Fig. 8.1). The 1700 km² middle Lerma

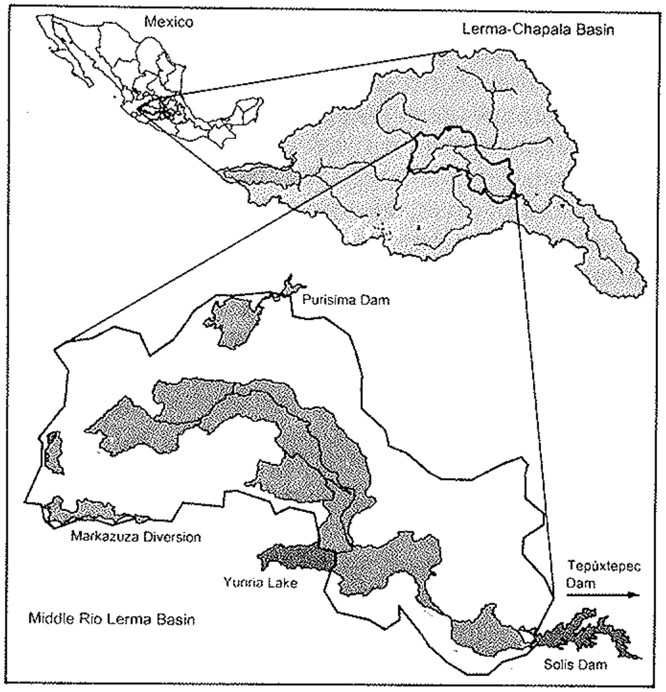

*Fig. 8.1: Middle Río Lerma Basin (with Alto Río Lerma Irrigation District)*

comprises 150,000 ha of irrigated area. The Alto Rio Lerma Irrigation District (ARLID, 112,000 ha command area) is supplied by surface water from four principal reservoirs (Solís, Tepúxtepec, Purísima, and Yuriria) in addition to groundwater. Because ARLID is the largest district within the Lerma–Chapala basin and located very much at its centre (see Fig. 8.1), these results can be considered representative of the basin as a whole.

ARLID takes approximately 44 per cent or 880 MCM of all the water stored for use by the irrigation districts in the Lerma–Chapala basin. There are roughly 24,000 water users with 55 per cent classified as communal farmers (*ejidatarios*) and 45 per cent as small private growers. The average landholding is 5 ha. Mean yearly evaporation is around 2000 mm. The dry winter season with approximately 80 mm of rainfall, starts in November and ends at the end of April. Rainfall in the spring/summer and second seasons, from May until November, is approximately 670 mm. Wheat and barley are normally grown during the dry winter season, while sorghum, maize and beans are the main crops grown in the wetter summer season. Farmers with access to groundwater tend to grow more vegetables (Kloezen and Garcés 1998). The irrigation district is subdivided into eleven units, referred to as modules. An individual Water User Association (WUA) manages each module. The irrigation network comprises 475 km of main irrigation canals and 1658 km of secondary and tertiary canals. Likewise, there is a network of approximately 1031 km of drainage canals. In addition, there are 1714 deep wells serving 35,075 ha. Roughly 80 per cent of the wells in operation in the basin are for agricultural purposes (Chávez 1998).

A number of smaller farmer-managed irrigation systems (*unidades*) irrigate an additional 38,000 ha command area from a combination of sources, principally groundwater (for statistics on the national breakdown of districts and *unidades*, see Garcés-Restrepo *et al.* 1996). Future IWMI research on the *unidades* will attempt to characterize these in sufficient detail to be able to distinguish water management and cropping practices from those prevalent in the districts.

Six aquifers or hydro-geological units, as identified by the Mexican National Water Commission (CNA, Comisión Nacional del Agua), underlie the middle Lerma basin. The aquifers are not strictly independent since there are no strictly impermeable geological barriers that separate them. However, for management purposes it is more convenient to deal with these 'fractions' or 'units'. In general terms, the first couple of hundred metres from the surface are composed of

alluvial and lacustrine materials: gravel, sand, silt, and clays, which form interconnected layers of irregular geometry and grading. The lower layers, several hundred metres in depth, are composed primarily of basaltic rocks and rhyolite tuff limited at the bottom by andesite and red conglomerate strata of low permeability (Chávez 1998). The aquifers are naturally recharged through rainfall infiltration and surface run-off, the latter both in mountainous areas and along the main riverbeds. To this natural component of the recharge, a human-derived component stemming from agricultural development needs to be added: the water derived for irrigation from the Lerma and the Laja rivers creates an incidental recharge generated by the conduction and distribution losses and the infiltration from excessive irrigation applications.

In previous research (from 1995 to 1996), IWMI calculated $\mathrm{RWS}_i$ at different levels in ARLID. Actual, planned and reported values of $\mathrm{RWS}_i$ were obtained at the system, module, and on-farm levels. Measurements were made to represent land tenure arrangements (*ejido* vs. private) and water sources (canal vs. well). In addition, the research layout followed the traditional head-middle-tail approach in the irrigation network. The results are summarized in Table 8.1. It is seen from the table that the irrigation district operated during the winter 1995–6 and the summer 1996 seasons, under conditions of relatively abundant water availability. It was possible for the system to meet crop water requirements with a margin of safety, as indicated by the $\mathrm{RWS}_i$ value at different district levels. Two other important results can be derived from the table: $\mathrm{RWS}_i$ values for private wells are generally lower than those for canal water in winter, but high for summer. However, given that the $\mathrm{RWS}_i$ values for canals are calculated at their offtake points, while those for the private wells represent on-farm level water supply, it is concluded that the farmers who use wells use more water.

*Table 8.1: Irrigation Relative Water Supplies ($\mathrm{RWS}_i$) for the Alto Río Lerma Irrigation District*

| *Water source* | *Season* | *ARLID district* | *Cortazar module* | *Salvatierra module* | *Cortazar on-farm* |
|---|---|---|---|---|---|
| Surface Irrigation | Winter 95–6 | 2.4 | 2.1 | 4.4 | n.a. |
| | Summer 96 | 1.9 | 1.9 | 2.0 | 1.8 |
| Private Wells | Winter 95–6 | 2.1 | 2.1 | 2.1 | n.a. |
| | Summer 96 | 2.2 | 2.2 | 2.3 | 1.8 |

(Adapted: Tables 3 and 7a, Kloezen and Garcés 1998).
n.a. = not available.

Two reasons explain this. First, private well owners generally do not wait for the rains but start irrigating as soon as they can. As a result of the late onset of rainfall during the summer of 1996, private well owners had already completed one irrigation, which explains the slightly higher actual $\text{RWS}_i$ summer values for wells as compared with surface water. Second, owing to subsidized energy tariffs the cost of pumping water had not yet exceeded the cost of surface water and as such, this has never been an incentive for well owners to economize on water (Kloezen and Garcés 1998). Finally, the difference in RWS values for surface irrigation between the two modules suggests quite different management approaches. The study revealed that Salvatierra's management set-up needs to be upgraded and that the existing 'relaxed' management has led to significant deterioration of the infrastructure. These data, particularly for the ARLID, compare well with the $\text{RWS}_b$ and $\text{RWS}_i$ values calculated in the present analysis, as shown in Table 8.2.

*Table 8.2: Basin and Irrigation Relative Water Supplies for the Middle Lerma Basin*

| *Year* | *$RWS_b$* | *$RWS_i$* |
|---|---|---|
| 1982–3 | 1.89 | 2.50 |
| 1983–4 | 1.89 | 2.32 |
| 1984–5 | 2.23 | 2.73 |
| 1985–6 | 2.34 | 2.84 |
| 1986–7 | 2.04 | 2.39 |
| 1987–8 | 1.52 | 2.09 |
| 1988–9 | 1.67 | 1.91 |
| 1989–90 | 1.69 | 2.06 |
| 1990–1 | 1.92 | 3.94 |
| 1991–2 | 1.96 | 2.53 |
| 1992–3 | 1.95 | 2.26 |
| 1993–4 | 2.09 | 2.28 |
| 1994–5 | 1.92 | 2.21 |
| 1995–6 | 1.92 | 2.15 |
| 1996–7 | 1.94 | 2.04 |
| 1997–8 | 1.54 | 1.93 |
| Average | 1.91 | 2.39 |
| St. Deviation | 0.22 | 0.49 |

The IWMI Mexico Programme undertook field research in the middle Lerma basin to determine the fate of excess water by quantifying the magnitude of drainage flow and pounding 'losses'. Two lateral canal command areas, each 250 ha in area, which are conjunctively irrigated from surface and groundwater sources have been identified where daily field measurements of all inflows and outflows are made. It is not our intent here to describe the details of the field measurement programme; however, it is important to indicate that the results reinforce our contention that the 'real water losses' are minimal. During the May–November 1998 rainy season, drainage outflow, which occurred primarily during storm events comprised only 5 per cent of the outflows from the field area, ET was 66 per cent and soil moisture change accounted for 5 per cent. The evaporative loss resulting from pounding was negligible, and 24 per cent of the outflow was calculated to recharge the aquifer. On the other hand, pumping rates were sufficiently high so as to result in net aquifer extraction as described in this essay.

## STATEMENT OF THE PROBLEM

In water-short river basins, such as the middle Lerma, exploitation of water resources currently exceeds the renewable annual supply. Intra-annual variations in runoff may alleviate or exacerbate water availability in the short term; however, the medium- and long-term effects are clearly significant only for the aquifers. In other words, a condition of low surface water supply can be overcome in just one year of high rainfall and runoff, whereas the accumulated deficit of years of aquifer overexploitation will similarly take years to reverse. Based on the reasoning and data we show here, modernization programmes to make water use more efficient are likely to have adverse impacts on aquifer levels in basins with similar conjunctive surface–groundwater characteristics as described here.

Nevertheless, reduced groundwater recharge resulting from more efficient surface water management implies a number of important tradeoffs with more than purely physical consequences. We refer specifically to social equity and economic productivity considerations, e.g. who irrigates with water from each source, and what costs and benefits are accrued. In the middle Lerma basin, the *ejido* sector (with smaller landholdings producing primarily cereals) is more dependent on surface water than the private sector (commercial farms with a greater degree of diversification in vegetable production for export). Conversely, groundwater tends to be the principal water source for private growers, although some *ejido* production units have access to groundwater. In this context, the present arrangement of a 'leaky' surface water supply system coupled with the large irrigation depths observed in the field (Kloezen *et al.* 1997) amounts to an indirect water transfer from the *ejido* to the private sector. While the constraints to producing higher-value crops with surface water are many (including poor access to credit), lack of flexibility in the scheduling of surface deliveries represents a primary water management limitation. At the same time, it appears as though pumping costs still do not represent a major cost constraint in the production of higher-value vegetables (primarily broccoli, cauliflower, peppers, carrots, strawberries, etc.) and fodder (alfalfa) crops.

The trend towards increased water shortages has resulted in higher inter-sectoral competition for the resource. In this regard, the urban sector has some advantage over others, given existing policy priorities (not always clearly justified), higher economic capacity and sheer demographic numbers. This situation has contributed to migration from rural areas toward the cities and the corresponding deterioration of the quality of rural life.

As in many other areas of the country, the extraction of groundwater in the basin began, on a large scale, in the early fifties driven by urban growth, industrial development and emerging irrigated agriculture. During this decade and the next, hundreds of wells were sunk to extend the area under irrigated agriculture or to complement irrigation requirements in areas already under irrigation. Through time, the fall in static water levels led to the need to sink deeper wells: indigenous water buckets (*norias*) were soon displaced by wells up to 100 m deep. Nowadays, depths between 200 and 400 m are not uncommon, and in the Salamanca area depths of 500 to 1000 m have been reported (Chávez 1998). The resulting drawdown of water levels has also affected small surface water impoundments, which lose their storage rapidly through percolation.

The principal effects of over-exploitation, or groundwater mining, in the basin include:

- increased costs of groundwater exploitation related to deeper wells, large motors or pumps and higher energy consumption;
- lower discharges and efficiencies of older devices;
- subsidence, settling and terrain fissures; and
- deterioration of water quality due to rapid transport of industrial contaminants and increased use of fertilizers and pesticides.

As static groundwater depths approach 60–80 m in many of the aquifers (with dynamic depths greater than 100 m), the need for well rehabilitation will soon exert cost constraints, even for the production of higher-value crops. A number of the aquifers are underlain by deeper constrained and semi-constrained strata with piezometric levels reportedly in the range of current static levels, e.g. at 100–150 m in the aquifers being exploited (J.V., local well equipment supplier, personal communication 1998). This may lead to false optimism that operational costs will be stable (once the investment has been made to drill into the deeper aquifer). It is our view that continued groundwater mining will deplete the present aquifers to a point where all but the highest value crops cease to be profitable. Given that the installed electricity generation capacity in Mexico will soon be surpassed by demand, unit energy costs will invariably increase. The only safe conclusion that can be drawn is that water scarcity from both surface and groundwater sources in the middle Lerma is inevitable in the short to medium term (10–20 years), and that this future scenario will only be hastened by programmes to make surface water irrigation more efficient.

## MODEL DESCRIPTION

A simple conjunctive surface water–groundwater model was developed to simulate the behaviour and response of the middle Lerma basin to climatic processes and water allocations. The primary objective was to characterize the influence of irrigation water management practices on groundwater levels, in order to understand the implications of alternative surface water management and cropping scenarios for groundwater. Based on a vertical water balance, the model accounts for changes in groundwater storage resulting from the difference between inflows—both natural (precipitation and river flow) as well as reservoir releases for irrigation within the simulated system—and outflows including river flows, irrigation releases for areas outside the system and the ET demand of crops and natural vegetation. The residual term in the mass balance is net change in aquifer storage, expressed as:

$$\Delta S = P + (Q_{ri} + Q_{si}) - (Q_{ro} + Q_{so}) - (ET_C + ET_V)$$

where
$\Delta S$ is net change in aquifer storage,
P is precipitation (effective),

$Q_{ri}$ is river inflow,

$Q_{si}$ is surface irrigation inflow (reservoir release),

$Q_{ro}$ is river outflow,

$Q_{so}$ is surface irrigation outflow (downstream release to irrigated area outside the system),

$ET_c$ is crop evapotranspiration, and

$ET_v$ is vegetation (non-crop) evapotranspiration.

The change in static water level is calculated as:

$$\Delta h = \frac{\Delta S}{Ak}$$

where

$\Delta h$ is the change in static water level,

$\Delta S$ is as defined above

A is the aquifer area, and

k is the aquifer storage coefficient.

The system boundaries have been defined as the spatial limits of the irrigated area for which monthly inflow and outflow data are available. We recognize that urban pumping places additional demand on the aquifer; because of high return rates (in the range of 70 per cent), this is not considered in the model. On the other hand, with the spatial concentration of wells in urban areas, there is a pronounced cone of depression in those areas.

An annual mass balance timestep was used to simulate basin response to agricultural water demand. The historical flow and cropping data were checked and found to be consistent and reliable. The following parameters were calculated or estimated, based on our knowledge of the study area:

- 10-day reference $ET_0$ and evapotranspiration coefficients for crops, trees, fallow (uncultivated) land, and bare soil (between crops) are based on CROPWAT (FAO 1996; Doorenbos and Pruitt 1975),
- area under trees = 10 per cent of the total area, and
- aquifer storage coefficient, k = 0.1. Values are reported in the range of 0.03–0.2 (CEASG, unpublished data, 1998).

The model was verified using measured static water levels from 398 wells in the six aquifers underlying the middle Lerma basin study area (INEGI 1998). For the 1982–98 simulation period, the average simulated decline was 2.12 m/year (yearly results are presented below with the water management scenarios). The simulated decline compares favourably to the average measured decline of 1.81 m/year (for the first part of the simulation period), as shown in Table 8.3a, which presents data on declines for those aquifers in the study area for the dates which cover the simulation period. Table 8.3b shows that additional

*Table 8.3a: Groundwater Trends:*
*Aquifers Studied, Simulation Period*

| *Aquifer* | *Period analysed* | *Decline* (m/year)* | $r^{2**}$ | *n wells* |
|---|---|---|---|---|
| Tarimoro | Jul 82–Aug 83 | 1.62 | 0.6186 | 13 |
| Jaral del Progreso | Feb 80–Aug 90 | 1.81 | 0.6588 | 39 |
| Acámbaro | Nov 82–Dec 87 | 3.30 | 0.8293 | 14 |
| Presa Solís | Sep 80–Aug 85 | 1.51 | 0.7057 | 81 |
| Irapuato–Valle de Santiago | Apr 81–Oct 85 | 2.13 | 0.6879 | 23 |
| Pénjamo–Abasolo | May 81–Jun 86 | 1.80 | 0.7046 | 59 |
| Average | | 1.81 | | |

* Beginning of period analysed is taken as reference water level = 0.
** All regression results are significant at $p < 0.001$.

*Table 8.3b: Groundwater Trends:*
*Regional Aquifers, Simulation Period*

| *Aquifer* | *Period analysed* | *Decline* (m/year)* | $r^{2**}$ | *n wells* |
|---|---|---|---|---|
| San Miguel de Allende | Jul 80–Feb 86 | 1.68 | 0.8008 | 8 |
| Tarimoro | Jul 82–Aug 83 | 1.62 | 0.6186 | 13 |
| Celaya | Oct 80–Dec 90 | 1.79 | 0.6873 | 103 |
| Jaral del Progreso | Feb 80–Aug 90 | 1.81 | 0.6588 | 39 |
| Acámbaro | Nov 82–Dec 87 | 3.30 | 0.8293 | 14 |
| Presa Solís | Sep 80–Aug 85 | 1.51 | 0.7057 | 81 |
| Cienega Prieta–Moroleón | Nov 85–Sep 96 | 1.22 | 0.6907 | 34 |
| Irapuato–Valle de Santiago | Apr 81–Oct 85 | 2.13 | 0.6879 | 23 |
| Silao–Romita | May 81–Nov 94 | 1.50 | 0.6410 | 97 |
| Pénjamo–Abasolo | May 81–Jun 86 | 1.80 | 0.7046 | 59 |
| León | Oct 82–Nov 90 | 2.30 | 0.7253 | 109 |
| Average | | 1.81 | | |

* Beginning of period analysed is taken as reference water level = 0.
** All regression results are significant at $p < 0.001$.

aquifers in the region are in similar processes of static groundwater decline (again for the simulation period only), while Table 8.3c shows similar historical trends (longer than the simulation period) in regional aquifers. Only wells with three or more static level measurements were used in the regression analysis. Figs 8.2–8.4 present time-series plots of three representative aquifers (for purposes of visual comparison, all groundwater plots in this chapter use the same axes scales). It should be noted that the number of wells plotted in these figures may differ from the number of wells used for the regression analysis in Tables 8.3a, 8.3b. The average declines of 1.81 m/year in both tables are purely coincidental.

Based on these results, we are confident that the model accounts for a representative set of physical hydrologic processes. Unfortunately, the Mexican government programme to monitor static water levels in pilot wells throughout the middle Lerma basin was suspended in the late eighties, with a few exceptions. Fig. 8.4 shows data for sixteen wells in the Silao–Romita aquifer from November 1994, which appear to indicate that static groundwater levels may have stabilized, or even increased slightly. While this would be a logical outcome of increasing energy costs (both as a result of declining water levels and increasing unit energy costs), the lack of data for the May 1986 to November 1994 period makes it difficult to draw a final conclusion. Time-series data for additional aquifers would need to be analysed to test such a hypothesis.

*Table 8.3c: Groundwater Trends:*
*Regional Aquifers, Historical Record*

| *Aquifer* | *Period analysed* | *Decline* (m/year)* | *$r^{2}$*** | *n wells* |
|---|---|---|---|---|
| San Miguel de Allende | Jun 76–Feb 86 | 2.10 | 0.7490 | 23 |
| Tarimoro | Sep 76–Sep 85 | 1.51 | 0.6525 | 18 |
| Celaya | Sep 76–Dec 90 | 1.00 | 0.7522 | 28 |
| Jaral del Progreso | Sep 76–Sep 90 | 1.97 | 0.7454 | 36 |
| Presa Solís | Aug 76–Aug 85 | 1.51 | 0.6525 | 18 |
| Irapuato–Valle de Santiago | Jul 76–Oct 85 | 1.93 | 0.6373 | 51 |
| Silao–Romita | Nov 77–Nov 94 | 2.26 | 0.7176 | 67 |
| Pénjamo–Abasolo | Nov 78–Jun 86 | 2.58 | 0.7833 | 90 |
| Average | | 2.06 | | |

* Beginning of period analysed is taken as reference water level = 0.
** All regression results are significant at $p < 0.001$.

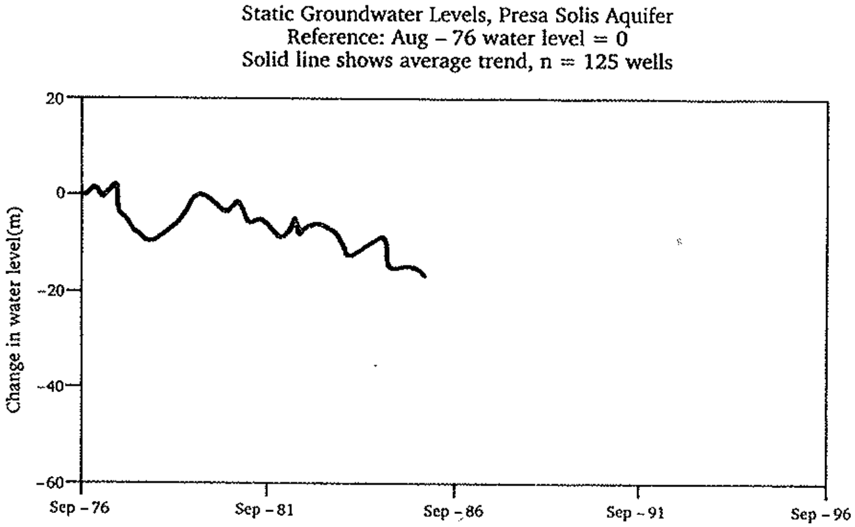

*Fig. 8.2: Measured Static Groundwater Levels, Presa Solís Aquifer*

*Source: INEGI, 1998*

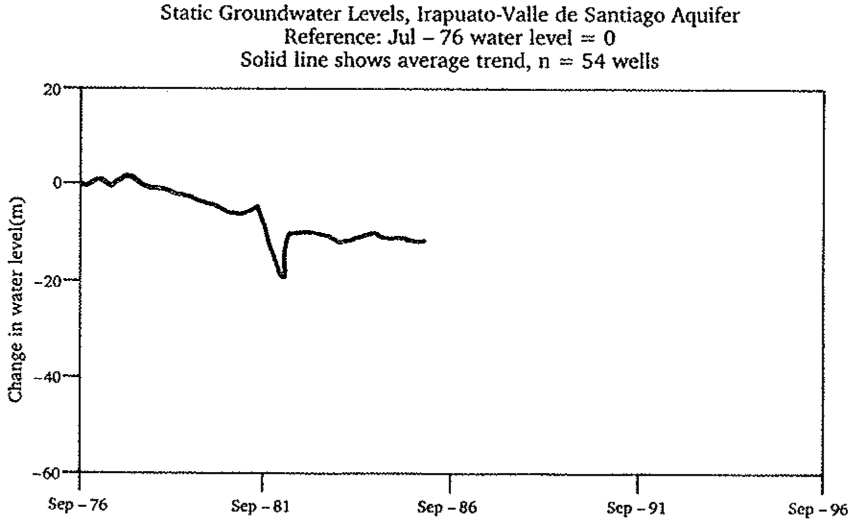

*Fig. 8.3: Measured Static Groundwater Levels, Irapuato–Valle de Santiago Aquifer*

*Source: INEGI, 1998*

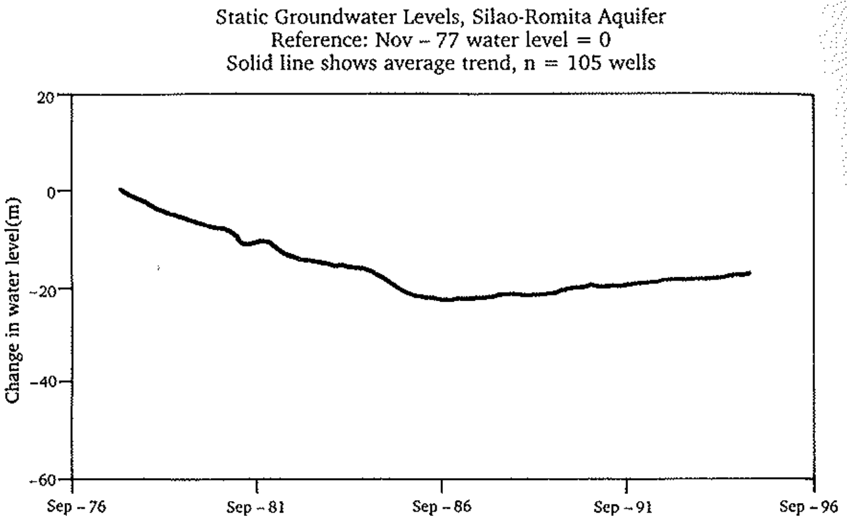

*Fig. 8.4: Measured Static Groundwater Levels, Silao–Romita Aquifer*
*Source: INEGI, 1998*

## ALTERNATIVE CROPPING AND WATER MANAGEMENT SCENARIOS

To explore the implications of alternative crop and water management practices for groundwater levels in the middle Lerma basin, the model was used to simulate various scenarios. The five cropping scenarios were considered to be feasible from the perspective of farmer adaptation to economic and climatic conditions. Two of the three water management scenarios were considered to be feasible based on analysis of historical reservoir storage data, while the third was not considered feasible, but is presented below so as to comment on the groundwater impacts of surface water management. The 1982–98 historical cropping patterns for the middle Lerma basin were analysed, and the average ($\bar{A}$) and standard deviation ($\sigma A$) were calculated for each of the following:

- area under grains in fall/winter;
- area under vegetables in fall/winter;
- area under grains in spring/summer and second season; and
- area under vegetables in spring/summer and second season.

Table 8.4 summarizes the five cropping scenarios (S1–S5) and three water management scenarios (S6–S8) simulated. Actual historical

hydrologic conditions (rainfall, river flow, and reservoir releases) were used to assess the groundwater response to each of the cropping scenarios. S1 reflects a reduction in agricultural production that could result from increased inter-sectoral competition over water. S2 is the average case, and should result in static groundwater declines similar to those simulated for actual cropping patterns and to measured groundwater trends. S3 is an unlikely scenario of increases in both grain and vegetable production (this will be shown to have the most extreme effect on groundwater levels). S4 and S5, different degrees of conversion of grain production to vegetables, represent a trend that is likely to result from the signing of the North American Free Trade Agreement (NAFTA). In this scenario, large-scale grain production units in the United States and Canada (with their built-in subsidy and price support structures) out-compete Mexican grain production, but climatic and labour conditions favour the production of vegetables in Mexico. This trend is already evident in the middle Lerma basin, where commercial production units are increasingly entering into direct export contracts with foreign buyers (local informants, personal communication 1998–9).

*Table 8.4: Scenarios Simulated*

| *Scenario* | *Area under grains* | *Area under vegetables* | *Basin Surface* RWS$_b$ |
|---|---|---|---|
| S1 | low | low | actual |
| S2 | average | average | actual |
| S3 | high | high | actual |
| S4 | low | high | actual |
| S5 | very low | very high | actual |
| S6 | actual | actual | actual + 10% |
| S7 | actual | actual | actual–10% |
| S8 | actual | actual | actual + 23% |

where
very low $= \bar{A} - 2\,\sigma_A$
low $= \bar{A} - \sigma_A$
average $= \bar{A}$
high $= \bar{A} + \sigma_A$
very high $= \bar{A} + 2\,\sigma_A$

The basin-level surface relative water supply RWS$_b$ is an indicator of water available relative to crop ET demand. Using the actual historical cropping patterns, three additional water management scenarios were simulated. S6 and S7 represent +10 per cent and –10 per cent changes in $\text{RWS}_b$, respectively, while S8 represents a +23 per cent change in $\text{RWS}_b$, as will be explained in the next section.

## RESULTS AND DISCUSSION

Scenarios S1–S7 represent changes in cropping and water management that we consider feasible. None of these scenarios resulted in the stabilization of static groundwater levels; in fact, all resulted in continuing declines. It is instructive, however, to consider which scenarios produced the highest rates of decline and which even reversed groundwater decline in years of high surface water supply. Further, these processes are clearly reflected in the calculated relative water supplies. On the other hand, S8 was designed to produce a zero average groundwater decline for the 1982–98 period.

The changes in static groundwater levels resulting from the five cropping scenarios with the historical hydrologic data are shown in Fig. 8.5; changes in static groundwater levels resulting from the three

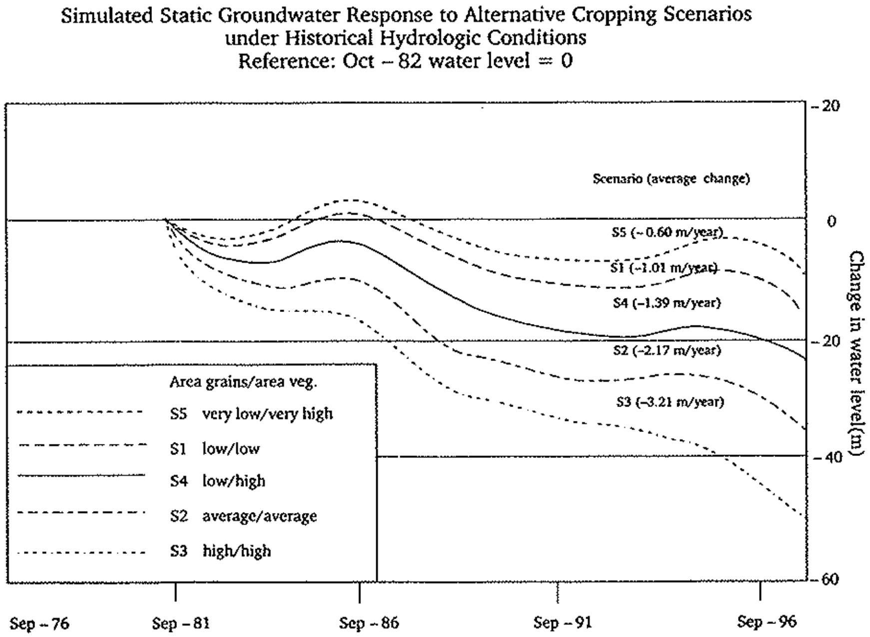

*Fig. 8.5: Simulated Static Groundwater Response to Alternative Cropping Scenarios*

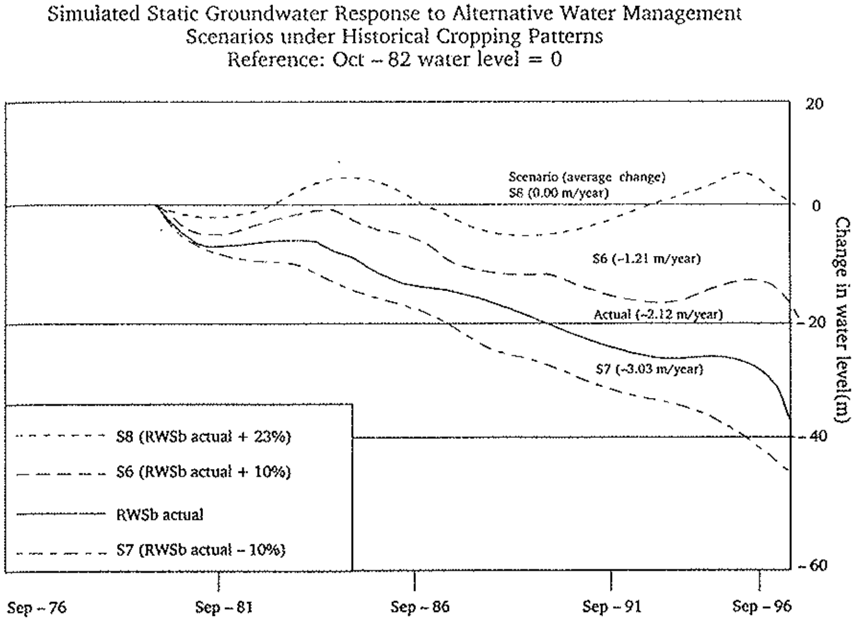

*Fig. 8.6: Simulated Static Groundwater Response to Alternative Water Management Scenarios*

water management scenarios are shown in Fig. 8.6. In Fig. 8.5, it is apparent that increased area under grains produces groundwater declines. This is a result of the high crop demand (over a longer period) as compared to vegetables. It should be noted that multiple vegetable crops within a single season were not considered, although this may become more common for economic reasons. Based on the definitions of very low, low, average, etc. defined for Table 8.4, the magnitude of changes in grain area is significantly greater than the magnitude of changes in vegetable area, e.g. the absolute values of the average and standard deviation for grain are considerably higher than for vegetables. Nevertheless, it is clear that producing grain in a water-short basin with high vegetable production potential is neither profitable nor sustainable from a water-resource perspective. The reasons for this continued practice have been discussed, being primarily the lack of flexibility in scheduling surface water deliveries for vegetables.

While it appears that a major shift to vegetable production would be beneficial from a groundwater perspective, this would imply significant changes in the current management arrangements for irrigated agriculture. Specifically, we refer to marketing, credit, transport, and support systems in general.

The three water management scenarios may require further explanation. For S6, the annual values of surface $\mathrm{RWS}_b$ were increased by 10 per cent, equivalent to 25 per cent increases in annual total reservoir releases ($\mathrm{Q}_{ri}$). While the other components of $\mathrm{TWS}_s$ (precipitation, outflows and crop ET) are not controllable variables, they were assumed to remain constant in volume, hence the only way to increase $\mathrm{RWS}_b$ is through increases in $\mathrm{Q}_{rig}$. For S7, $\mathrm{RWS}_b$ was decreased by 10 per cent (and $\mathrm{Q}_{ri}$ decreased by 25 per cent). Based on analysis of historical reservoir storage data for the 1950–96 period, the + 25 per cent change in $\mathrm{Q}_{ri}$ simulated in S6 appears to be the upper bound on feasible surface water management. Nevertheless, we considered an additional water management scenario, S8, that would produce zero average groundwater decline. The 23 per cent increase in $\mathrm{RWS}_b$ corresponds to a 57 per cent increase in reservoir releases, $\mathrm{Q}_{ri}$.

The results in Fig. 8.6 are perhaps more interesting from the perspective of conjunctive management of surface water and groundwater in river basins. The simulated groundwater decline resulting from actual $\mathrm{RWS}_b$ and historical cropping patterns is 2.12 m/year (as compared to average measure decline of 1.81 m/year, as discussed previously). The effect of reducing $\mathrm{RWS}_b$ by 10 per cent (S7), as through rehabilitation and modernization programmes to 'save water', produces significant additional groundwater declines, based on the explanation that increased pumping makes up for the 'saved' surface water. On the other hand, the groundwater response from increased surface water application in a 'leaky' basin (S6) is a marked slowing of groundwater declines. The 10 per cent increase in $\mathrm{RWS}_b$ corresponds to a 25 per cent increase in reservoir releases, $\mathrm{Q}_{ri}$. The results for S8 indicate that, under historical cropping patterns and hydrological conditions, $\mathrm{RWS}_b$ would have to increase by 23 per cent (equivalent to 57 per cent increase in $\mathrm{Q}_{ri}$) in order to stabilize groundwater levels. Fig. 8.7 synthesizes the results, and shows the relationship between changes in $\mathrm{RWS}_b$ and the corresponding $\mathrm{Q}_{ri}$ on the x-axis, and the resulting 16-year average groundwater decline on the y-axis. It should be noted that the straight linear relationship is a result of averaging sixteen years of fluctuating groundwater response.

During individual years, the cropping patterns may generate increases in groundwater levels. The relative water supplies resulting from different hydrologic conditions (with reference to the year that most closely corresponded to each condition) are presented in Table 8.5. Total surface water supply ($\mathrm{TWS}_s$) has been defined previously; the 1982–98 historical record was analysed to calculate the average and standard deviation ($\sigma_{\mathrm{TWS}_s}$).

The hump in Figs 8.5 and 8.6 for 1985–6 is the result of a particularly wet year, with high precipitation and net surface inflows. From Table 8.5, it is seen that RWS values (using both basin and irrigation definitions) for such conditions are very high. On the other hand, dry years with low total surface water supplies produce precipitous groundwater declines, even under low crop demand scenarios (see 1987–8 particularly for S5 or S1). In 1990–1, the year of average $\mathrm{TWS}_s$, the relative water supply values for irrigation are extremely high for all five scenarios, because the $\mathrm{RWS}_i$ index does not consider outflows that leave the basin, making the numerator extremely high. This clarifies our earlier statement that $\mathrm{RWS}_b$ better reflects the true supply and demand conditions in river basins. The results of the scenarios simulated clearly indicate that groundwater levels are extremely sensitive to changes in surface water management.

These findings run contrary to conventional thinking, and must be incorporated into the planning and implementation of rehabilitation

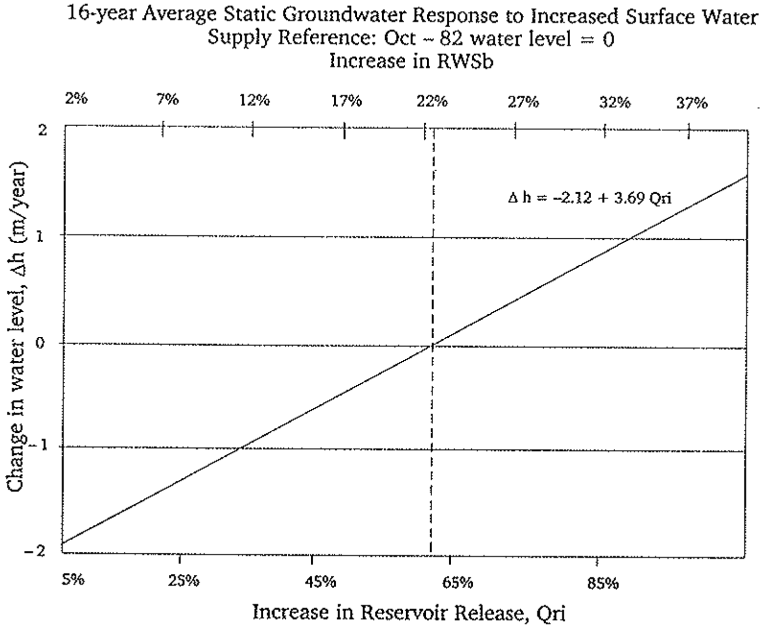

*Fig. 8.7: 16-year Average Static Groundwater Response to Increased Surface Water Supply*

and modernization programmes. The cornerstone of the current Mexican irrigation modernization programme is to tackle the problem of 'water losses' through a variety of strategies to improve water use efficiency at all levels. Our analysis indicates, however, that such an approach would negatively impact the declining groundwater resources.

*Table 8.5: Relative Water Supply Resulting from Alternative Cropping Scenarios Under Historical Hydrologic Conditions*

| *$TWS_s$* | *Year* | *S1* | | *S2* | | *S3* | | *S4* | | *S5* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *RWS* | *RWSi* | *RWS* | *RWSi* | *RWS* | *RWSi* | *RWS* | *RWSi* | *RWS* | *RWSi* |
| | | *b* | | *b* | | *b* | | *b* | | *b* | |
| Very low | 1987–8 | 2.08 | 2.86 | 1.38 | 1.90 | 0.91 | 1.26 | 1.91 | 2.63 | 3.11 | 4.28 |
| Low | 1989–90 | 2.34 | 2.87 | 1.55 | 1.90 | 1.03 | 1.26 | 2.15 | 2.63 | 3.51 | 4.29 |
| Average | 1990–1 | 2.92 | 6.00 | 1.93 | 3.97 | 1.28 | 2.63 | 2.68 | 5.51 | 4.36 | 8.97 |
| High | 1993–4 | 3.50 | 3.81 | 2.32 | 2.53 | 1.54 | 1.67 | 3.21 | 3.50 | 5.23 | 5.70 |
| Very high | 1985–6 | 3.96 | 4.81 | 2.63 | 3.19 | 1.74 | 2.11 | 3.64 | 4.42 | 5.92 | 7.20 |

where

very low = $\bar{T}\bar{W}\bar{S}_s - 2\,\sigma\,\mathrm{TWS}_s$
low = $\bar{T}\bar{W}\bar{S}_s - \sigma\,\mathrm{TWS}_s$
average = $\bar{T}\bar{W}\bar{S}_s$
high = $\bar{T}\bar{W}\bar{S}_s + \sigma\,\mathrm{TWS}_s$
very high = $\bar{T}\bar{W}\bar{S}_s + 2\,\sigma\,\mathrm{TWS}_s$

## CONCLUSIONS

Surface water and groundwater resources are linked, although the mutual influences are apparent only when viewed from a river basin perspective. This essay analyses historical cropping and water management data, combined with a simple water balance model, to assess the outcomes of several crop and water management alternatives. The results are highly illustrative of the tradeoffs involved in conjunctive surface water–groundwater systems. For the middle Lerma basin, increases in the irrigated area of vegetables coupled with decreases in the irrigated area of grains would have a beneficial impact on groundwater levels, but this presupposes major changes in current water management practices and institutional arrangements.

There is a need to continue or re-establish groundwater monitoring programmes in the water-short Lerma–Chapala basin. While previous studies indicated the high relative water supplies in the middle Lerma basin, it is apparent to us that this resulted from significant groundwater depletion. Definitions of water scarcity must account for groundwater trends.

The approach followed in this essay could be applied to other areas in Mexico in order to protect both surface and groundwater resources. In particular, the true extent of 'dry' and 'wet' savings must be evaluated. Furthermore, the specific results strongly indicate the need to assess more carefully the groundwater impacts of irrigation modernization programmes under way or being planned in Mexico.

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