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REPORT

Evolution and sustainability of groundwater use from the Ica aquifers for the most profitable agriculture in Peru

Enrique Fernández-Escalante[1] · Stephen Foster[2] · Roberto Navarro-Benegas[3]

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Abstract

The Ica area of south-eastern Peru has evolved rapidly since the late 1990s into the most advanced agricultural development in the country. The intensive use of waterwells for year-round irrigation, primarily of asparagus, is the basis for an export industry worth about US$ 6,000 M/a, but one which is threatened by serious groundwater sustainability concerns. The public water-resource administration and private agricultural developers are beginning to confront the problem, which has already had a significant social cost, through developing measures to improve the groundwater balance whilst assuring agricultural production. This report presents the long-term evolution of land management and groundwater use in the area, and considers the feasibility of applying an adaptive and integrated water resources management (IWRM) approach to the system, with particular attention to managed aquifer recharge techniques.

Keywords Peru · Hyper-arid regions · Groundwater recharge · MAR · Agricultural irrigation

The Ica area: an introduction

Ica, with an urban population of 282,000 in 2017, must be one of the world's largest human settlements in a hyper-arid region, with rainfall less than 10 mm/a. It is situated at about 400 m above sea level (ASL) on the desert coastal strip of Peru, some 300 km south of the capital Lima and 40 km from the Pacific Ocean shoreline (Fig. 1). The only source of water for the city and surrounding agricultural areas derives from the Ica River, which rises in the neighbouring Andean mountain-chain and in the Ica area infiltrates to form two important groundwater systems—the Ica Valley and Pampa Villacurí aquifers.

In recent years the exceptionally sunny climate has attracted a large agro-industry to the area, and intensive waterwell abstraction from these groundwater systems is the basis for year-round irrigated agricultural production (mainly for asparagus, avocado and table-grapes). The total area under agricultural cultivation more than doubled between 1998 and 2010 (to 29,500 ha), and grew further in the subsequent years. An additional source of revenue is tourism, with the adjacent Huacachina Oasis, well-developed desert dunes and the Ica Regional Museum (exhibiting both pre-Inca and Spanish-colonial remains) attracting many visitors.

Enrique Fernández-Escalante is Co-Chair of the International Association of Hydrogeologists (IAH) Commission on Managing Aquifer Recharge, and Stephen Foster is IAH Past President (2004–2008)

✉ Stephen Foster
DrStephenFoster@aol.com

[1] TRAGSA (Empresa de Transformacion Agraria S A), Madrid, Spain

[2] University College London, London, UK

[3] Junta de Usuarios del Acuifero de Valle de Ica (JUASVI), Ica, Peru

Groundwater occurrence and use

Since the Ica Valley and Pampa Villacurí aquifers have a hydraulic connection (with some subsurface flow from the former to the latter; Fig. 2), they have to be considered technically as in unison, but their management needs reveal significant differences:

- **Ica Valley Aquifer**: Recharged directly and indirectly by the Ica River and underlying an important regional capital and desert oasis, it being essential that its groundwater use for export agriculture is managed adaptively through supply-side and demand-side measures to achieve long-term physical sustainability
- **Pampa Villacurí Aquifer**: Occurring in a desert area with very limited current natural recharge and partly underlain by the saline Pisco Formation, its use being confined to

Fig. 1 Location of the investigation area in Peru

crop irrigation for the large-scale agro-export industry, whose sustainability can only be achieved by transfer and recharge of part of the excess flows in the Ica and Pisco rivers and must be subjected to detailed socioeconomic analysis.

The neighbouring Lanchas Aquifer to the northwest exhibits some similarities to that of the Pampa Villacurí regarding its configuration (but its salinity is higher due to halite and gypsum lenses). It is not considered further in this report, although it is sometimes dealt with as part of the same system by Agência Nacional del Águas (ANA).

Asparagus cultivation and groundwater

The intensive cultivation of asparagus was introduced to Peru late in the 1990s and it now dominates world trade in the fresh product. Almost all (95%) of Peru's asparagus production is concentrated around Ica (Fig. 3), where the cultivated area is now more than 15,000 ha. Ica is one of the few places in the world where high-quality fresh asparagus can be produced all year round, due to the warm temperatures and sandy soils. Optimum growing conditions are achieved by conditioning the desert sands with manure and irrigating with groundwater. Asparagus water requirements are in the order of 1,500−1,700 mm/a, with consumptive use of groundwater for this crop alone in the Ica area put at some 225–255 Mm^3/a.

The current value of asparagus production (both fresh and preserved) is put at about US$ 6,000 million/a, with the industry having created around 20,000 jobs in a socially poor area and achieved over 35% female occupation (Muñoz 2016). These figures make Ica the 4th department in Peru in terms of gross income per cápita, and 2nd in terms of employment (INCORE 2019), due almost entirely to the export of asparagus.

Most asparagus is being produced by large agro-export enterprises on farms of 400–1,500 ha area, with smaller amounts from medium-sized farms of 10–100 ha. Between 1997 and 2005, the arrival of agro-export companies on the Ica scene has produced a number of important changes in land and water management (Hepworth et al. 2010; Wāhlin 2018):

- Major amplification of the frontier of cultivated land into previously desert areas (Fig. 4)
- Abandonment of traditional spate irrigation during times of high flow (*avenidas*) of the Ica River to avoid damaging irrigation infrastructure, which greatly reduces groundwater recharge and leads to a tendency towards drier soils

Fig. 2 Hydrogeological cross-section of the Ica aquifers

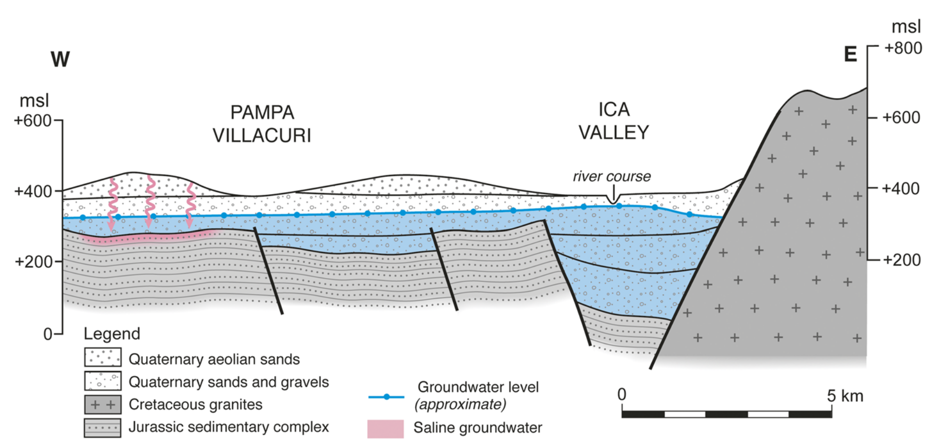

Fig. 3 Typical development of intensive export agriculture in the Ica Valley

- Increased hydraulic imbalance in the groundwater systems, which has led to accelerating water-table decline and the drying-up of waterwells of smaller farmers (typically of 30–40 m depth), who either cannot afford to deepen them or have regulatory constraint
- Purchase of groundwater abstraction rights from small farmers (often for waterwells that have dried-up due to falling water table) at prices in the range US$ 80–100,000, and their questionable geographical transfer to new locations
- Transfers from the Atlantic Basin, crossing the Andes though tunnels such as the Choclococha and Supramayo

The hydrologic situation has forced the water authorities and private enterprises to improve water-resource management, by the integration of water transfers, the development and maintenance of irrigation canals, regulating the flow of the Ica River, and the promotion of managed aquifer recharge (MAR), although there is still insufficient recharge to balance groundwater overexploitation.

Characteristics of the Ica aquifers

The Ica Valley Aquifer comprises a sequence of Quaternary unconsolidated fluvial-alluvial sediments, deposited by the Ica River, with an area of about 335 km^2 (Fig. 5). The depth to underlying bedrock is 60–500 m (Fig. 2) and the thickness of exploitable saturated aquifer currently is in the range 20–190 m.

Some 33 aquifer pumping tests have been conducted in three separate zones of the Ica Valley (ANA 2012, 2017) and indicate that the formation is an essentially unconfined, unconsolidated, porous system with transmissivity (T) in the range 400–3,800 m^2/day, a hydraulic conductivity (K) of 130–1,300 m/day and a specific yield ranging up to 12% (ANA 2017). In the San José de los Molinos and Subtanjalla districts its T is consistently above 2,000 m^2/day, whilst further south in the Ocucaje district it reduces to about 1,100 m^2/day.

The Pampa Villacuri Aquifer (Fig. 2) comprises a thinner sequence of aeolian and fluvial sediments with much less data, but its K is put in the range 70–500 m/day (ANA 2012).

The groundwater equipotential lines for the Ica Valley Aquifer below the Pampa Villacuri diversion, are directed southwards downstream through the highly transmissive alluvial formation (Fig. 2). The estimated residence time for the shallow aquifer between La Achirana and Ocucaje is about 450 days (Navarro and Fernández 2017).

Surface-water availability

Since the beginning of automated measurement at the Samaca gauging station on the lower part of the Ica River (in Ocucaje District) in 2013, maximum flows have always occurred during March (with a highest instantaneous flow of 115 m^3/s on 27

Fig. 4 Pampa Villacuri from Cerro Prieto, Ica illustrating the expansion of the frontier of irrigated agriculture onto desert land

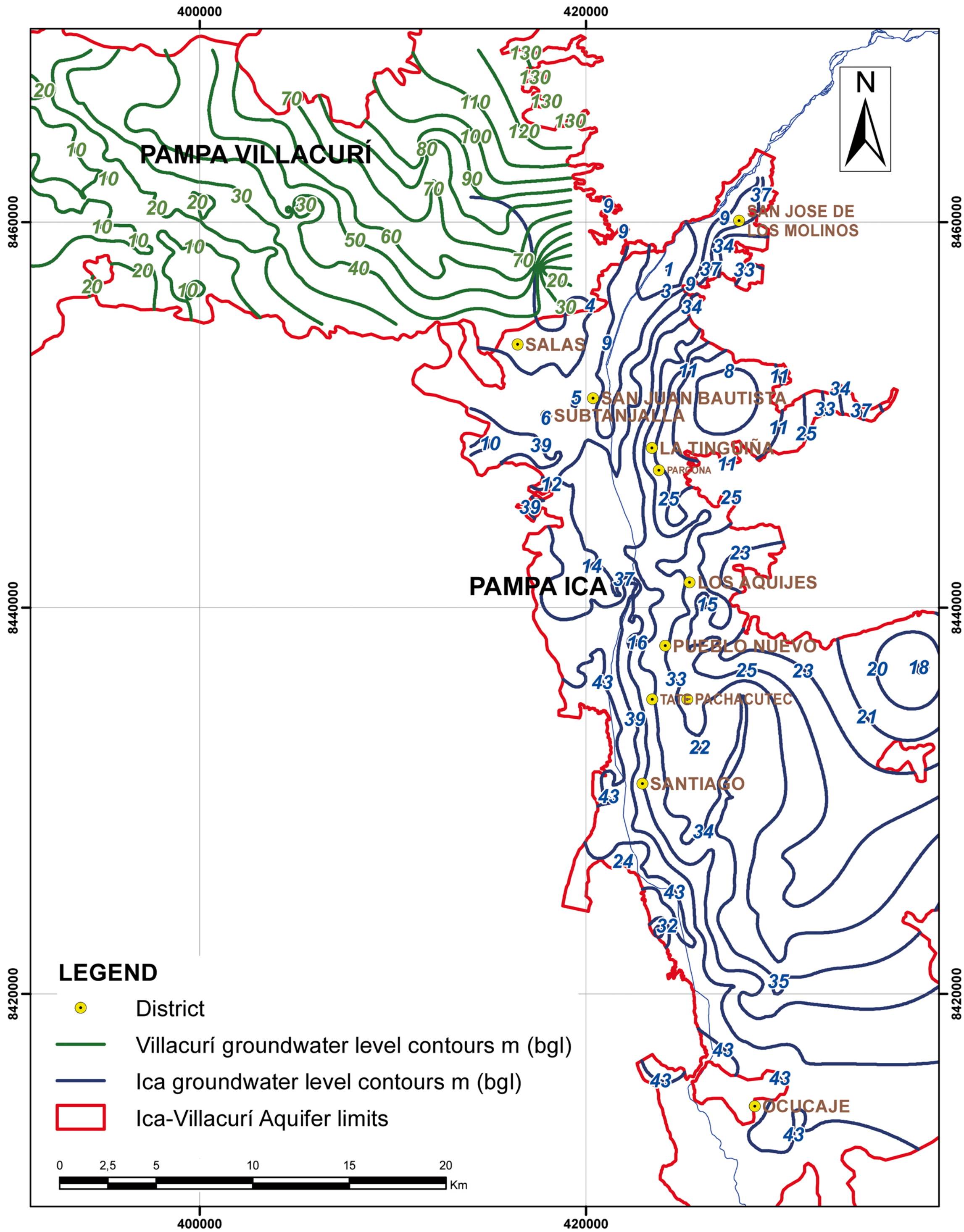

Fig. 5 Aquifer distribution and current water-table depths (m) of the Ica aquifers

March 2017), and with no flow outside the Andean rainy season of January–April or occasionally May (Table 1). These volumes do not include groundwater underflow in the alluvial deposits of the valley at the location of the gauging station.

During 2013–2017 the volume of river flow to the ocean is put at 183 Mm^3, and this gives an idea of the potential volume available for managed aquifer recharge higher up the valley. However, the extreme monthly and annual variability of this flow (Tables 1 and 2) also reveal the challenge of dealing with large volumes during short periods in the month of March. Moreover, the annual average river flow to the ocean during 2013–2017 is 36.5 m^3/a, less than the current rate of groundwater overexploitation.

Table 1 Total monthly discharges of the Ica River to the ocean as measured at the Samaca gauging station during 2013–2017 (Fernández 2019). Totals and averages are italicized

Month	Discharge (m^3)
January	16.5
February	22.1
March	128.2
April	16.0
Total 2013–2017	*182.8*
Average annual	*36.5*

Public water-supply provision

Since time immemorial the population of Ica have used groundwater. Prior to 1940 the underlying water table stood at about 2 m below ground level (bgl) with individual households obtaining their own private water supply by digging shallow (5–8 m deep) waterwells. In 1939 the municipality decided to commence offering a piped supply of limited coverage, because of pathogenic disease outbreaks associated with groundwater contamination from in-situ sanitation. They constructed three much-deeper waterwells (one of which is still in use), and during the following 50 years further waterwells were drilled to meet the steadily increasing demand.

The current water-service utility, EMAPICA, was founded in 1989 as an autonomous municipal company. While suffering major setbacks in the catastrophic flooding of 1998 and massive earthquake of 2007, today it operates 23 deep waterwells of both intra-urban and peri-urban location, and 2 upstream infiltration galleries, to produce some 17 Mm^3/a (47 Ml/day). These sources (rated individually at 15–60 L/s) supply a suite of distribution reservoirs serving about 200,000 of the urban population for at least 12 h/day, although in the outermost districts this reduces to 1 h/day. However, the negative impact on EMAPICA sources of the continually declining water table in the Ica Valley Aquifer must not be overlooked, and an assessment of their susceptibility to yield reduction and pollution vulnerability should be incorporated in a 'priority management action plan'. Ica is also serviced by an increasingly extensive mains sewerage system, that delivers wastewater to a group of stabilisation lagoons of 13-ha area at Cachiche.

Table 2 Total annual discharges of the Ica River to the ocean as measured at the Samaca gauging station during 2013–2017 (Fernández 2019)

Parameter	Year					Total
	2013	2014	2015	2016	2017	
Riverflow (m^3)	28.5	2.0	21.2	0	131.1	182.8

Evolution of groundwater resources

Ica Valley Aquifer

The first systematic groundwater study of the Ica area by Tajal Consulting in 1968 already noted local groundwater over-exploitation with a water-table decline of about 5 m in some zones, and this led to the declaration of a weakly enforced waterwell drilling ban (*veda*) in 1970 (Ministerial Resolution No. 468-70-AG). This was subsequently ratified and reinforced by various resolutions during 2008–2011 (Nos. 061-2008-AG and 554-2008-AG, 763-2009-ANA and 330-2011-ANA, with a tentative resource allocation of 190 Mm^3/a (that was subsequently increased to 250 Mm^3/a).

In Ica, traditional agriculture was in serious economic decline by the 1990s with land going out of production and irrigation infrastructure poorly maintained. That agriculture had involved the cultivation of grapes (for liquor production), cotton and olives (for oil production) under furrow irrigation with groundwater, following land spreading and flooding for aquifer recharge during periods of excess river flows (*avenidas*).

The arrival of the agro-export industry from the late 1990s changed the land-water management regime radically, cultivating mainly asparagus with some table-grapes and avocados under groundwater-fed ferti-irrigation, and the irrigated area of the valley expanded to 16,700 ha in 2010 (ANA 2012). This greatly increased demand (especially in the Santiago District where pumping in 2007 was estimated at 168 Mm^3/a for predominantly consumptive use) with an estimated total abstraction of 350–380 Mm^3/a. However, there remained substantial uncertainty in quantifying the rates of both consumptive use by irrigated agriculture and recharge by infiltration of surface water from the riverbed, seepage from irrigation canals, irrigated fields, and infiltration ponds.

The depth to groundwater is very variable, changing with the relief and current degree of over-exploitation (Fig. 2), and in the Ica Valley it ranges between 5 and 50 m bgl. In general terms, groundwater levels fluctuate seasonally with river stage, but with an overall tendency for continuous decline (Fig. 6). During 1998–2008, the water table dropped from 2 to 8 m (0.25–0.80 m/a on average) in the Ica, San Juan Bautista, Salas Guadalupe and Santiago Districts, whilst in La Tinguiña, Parcona, Los Aquijes and Pueblo Nuevo the fall was from 15 to 18 m (0.10–0.60 m/a; Navarro 2015). This trend appears to have persisted until the present but, due to the economic crisis and reductions in government funding, monitoring was reduced and data availability is more restricted. Currently about 75% of agricultural irrigators in the Ica Valley do not have sufficient water to satisfy their demand and some landowners have had to reduce or stop cultivation. As regards groundwater quality, the current monitoring network of 94 waterwells of up to 110 m depth indicates a mean groundwater nitrate concentration of 11 mg/L, $CaCO_3$ hardness of 68 mg/L and pH of 8.2.

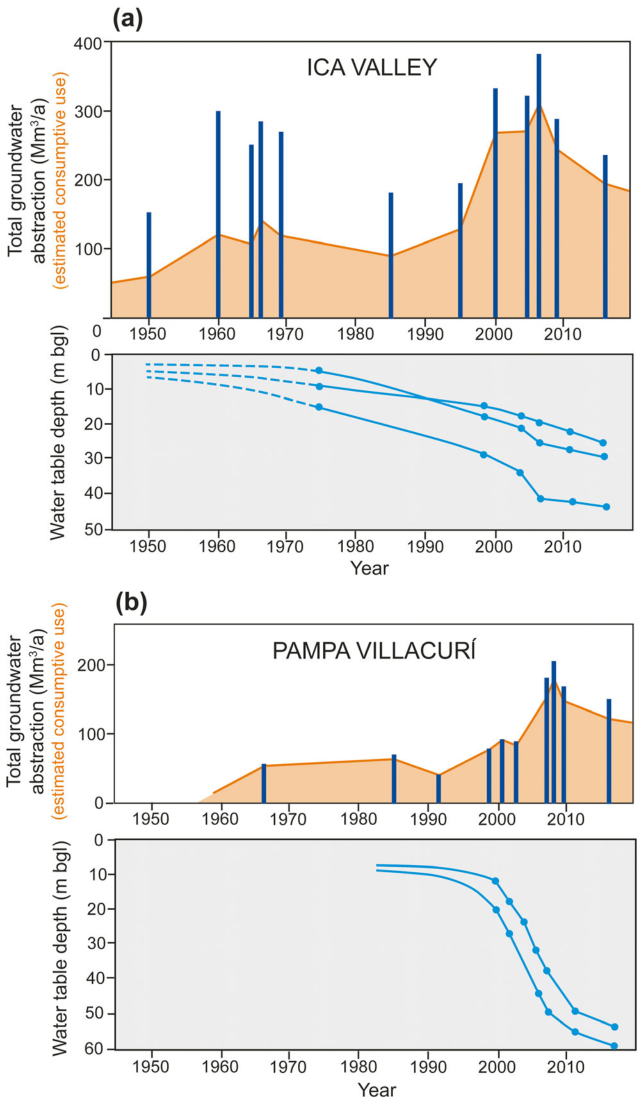

Fig. 6 Long-term groundwater abstraction data and water-table trends for the Ica aquifers: **a** Ica Valley Aquifer, **b** Pampa Villacuri Aquifer

Pampa Villacurí Aquifer

The Pampa Villacurí has currently 15,100 ha (of mainly asparagus with some paprika) under groundwater irrigation, which increased from 12,800 ha in 2010 (ANA 2012). But its aquifer receives only limited natural recharge through a subterranean inflow from the Ica Valley between Cerro Prieto and Cerro Soldado—estimated to be about 75 Mm^3/a from the results of numerical simulation. There is also possibility of some other minor highly sporadic (but unproven) inflows along the Rio Seco. With the arrival and intensification of agro-exportation enterprises and rural electrification (in 1992), consumptive use of groundwater in agricultural irrigation has probably increased from about 30 Mm^3/a in 1990 to 80 Mm^3/a in 2000, 160 Mm^3/a in 2008 and around 120 Mm^3/a in recent years.

Between 1998 and 2005, the water table on the Pampa Villacuri fell from 1 to 19 m bgl (0.15- to 2.4 m/a), as the evidence of a heavily overexploited aquifer (Fig. 6), but with an average decline of 0.45 m/a since recharge enhancement measures were initiated (ANA 2017). Despite the waterwell drilling ban of 2008, heavy resource over-exploitation appears to have continued with water-table decline at 2–3 m/a to about 50–70 m bgl (Navarro 2015).

Groundwater level decline has been accompanied by serious up-coning of saline groundwater (salinity to over 5,000 µS/cm) in the west of the aquifer from the underlying Pisco Formation at 100–150 m depth, which greatly reduces its utility for high-value cropping. Current groundwater quality indicates a mean nitrate concentration of 49 mg/L and pH of 7.9.

The situation of overexploitation of the Pampa Villacuri Aquifer continues to worsen with time, and the current waterwell drilling ban does not appear to be respected with the agricultural frontier continuing to expand. It is imperative that the authorities close illegal waterwells, implement a control program, and carry out awareness-raising activities.

Groundwater balance and modelling

The most recent groundwater resource investigation of the Ica aquifers by the World Bank for ANA (2017) estimates the recharge to the main Ica Valley Aquifer and Pampa Villacuri Aquifer to be 179 and 86 Mm^3/a, with the corresponding estimates of current gross abstraction being 231 and 142 Mm^3/a, respectively. This implies current rates of over-exploitation of 52 and 56 Mm^3/a, respectively. The recharge rate to these aquifers is greatly influenced by three factors, all of which have varied widely down the years:

- The volume of flow diversion from the Ica River, and from there to the Pampa Villacuri (currently estimated to be 60 Mm^3/a)
- The irrigation management on cultivated land, which determines the rate of infiltration returns to groundwater
- The effectiveness of MAR from infiltration ponds

It should, however, be noted that there is insufficient excess flow in the Ica River in most years to compensate for the current rates of aquifer overexploitation, and serious demand management measures will inevitably be required to reach a reasonable resource balance.

A preliminary combined Visual MODFLOW numerical model exists for the Ica Valley and Pampa Villacuri aquifers, which is reasonably calibrated spatially using 2002–2006 data with a gross groundwater abstraction of 375 Mm^3/a. However, the robustness of this model could be enhanced by endeavouring to reproduce the historical evolution of groundwater levels and abstraction since 1970, through interpretation of cropped areas, and crop and irrigation type (and their manifestation in terms of groundwater consumptive use) from satellite images and aerial photo archives, and then also covering the better documented period from 2007 to 2017.

Groundwater management measures

In an advisory mission to ANA of 2009, the *World Bank Groundwater Management Advisory Team* (GW-MATe) strongly recommended concerted action to supplement aquifer recharge from excess flows in the Ica River by reactivation of irrigation canals and water delivery to a large number of infiltration ponds in the valley. Such a MAR programme was seen as an essential complement to constraining the total groundwater abstraction and consumptive irrigation use through effective licensing and metering, and banning the construction of new waterwells.

Supply-side management

Since 2012, the *Junta de Usuarios del Valle de Ica* (JUASVI) and *de Río Seco*, with the support of the ANA, have annually promoted the construction of large numbers of infiltration ponds of about 2 m depth for intermittent use (Table 3; Fig. 7). As a result, the Ica area has become home to one of the largest scale MAR systems in the world. Water is diverted from the Ica River during the Andean rainy season by diversion dams at La Achirona and Macacona, then retained in decantation ponds, and later delivered to about 850 infiltration ponds (*pozas*) interspersed along the aquifer in plots of land borrowed from private land-owners (conscious of the fact that an increase of groundwater storage will favour their waterwell use for agricultural irrigation). A 4-day infiltration trial was conducted near La Achirana (Los Aquijes District) at a rate of 360 mm/day, confirming the general recharge potential.

In 2012 infiltration pond construction was restricted to the Aquijes District (Fig. 8), but in 2013 was extended to include the Pueblo Nuevo and Parcona districts, and in subsequent years the scheme was further extended and intensified. In 2015 JUASVI formulated a proposal that existing publicly owned land be provided to expand the recharge zone, and this led to a major increase in the number of ponds in 2016, although the lack of river flow in that year greatly reduced the infiltrated volume achieved (Table 3). However, in 2017, further ponds and micro-reservoirs were added to the system, and an infiltrated volume of almost 17 Mm^3 was achieved during January–May 2017 (Navarro and Fernández 2017).

Many social, technical and financial lessons have been learnt about the promotion of MAR and the construction of infiltration ponds. After 7 years' practical operation, it is realistic to assume an 'average wet period' of 120 days (with river water available for recharge) for which an infiltration pond of 0.5 ha will facilitate the recharge of about 0.2 Mm^3. If the current aquifer overexploitation is 52 Mm^3/a, another 120 ha of ponds will be required in suitable locations to achieve a groundwater balance. This is not considered feasible given the lack of suitable land, since most is usually cultivated. It will, therefore, be necessary to consider infiltration wells or galleries, or other techniques.

Another approach to estimating the magnitude of the 'groundwater balance problem' comes from considering the JUASVI experience during 2013–2017. If by 2017 an artificial recharge of 17.6 Mm^3 was possible from 864 ponds occupying 295 ha (Table 3), around 2,500 additional ponds would be needed to provide the required additional recharge.

On the Pampa Villacuri most attention is currently focused on possible schemes to transfer excess flows in the Rio Pisco (estimated at 120 Mm^3/a) by the construction of a new canal (of 46 km length) for recharging via infiltration ponds. There are, however, serious questions about how this (or any similar scheme) can be financed, given that regional government correctly expects a 50% contribution from beneficiaries, and it is not yet clear that this will be forthcoming. Meanwhile there is an urgent need to rationalise groundwater use rights, to stop the practice of transferring rights to distant locations when the original waterwell exhibits increasing salinity, and to consider backfilling certain waterwells to reduce their pumping depth and the salinity of groundwater extracted.

Currently the only water for MAR in this desert area comes from the Ica River via the Macacona and Quillogy canals, with a current maximum flow capacity of about 17,000 m^3/day. In 2013, a single infiltration pond of 0.64 ha was available fed by

Table 3 Evolution of MAR infiltration ponds in the Ica Valley during 2012–2017

Year	No. of infiltration ponds	Total infiltration Area (ha)	Average pond size (ha)	Infiltrated volume (Mm^3)
2012	41	22	0.53	0.6
2013	89	37	0.42	1.5
2014	125	59	0.47	3.5
2015	192	70	0.36	11.5
2016	659	234	0.35	2.0
2017	864	295	0.34	16.6

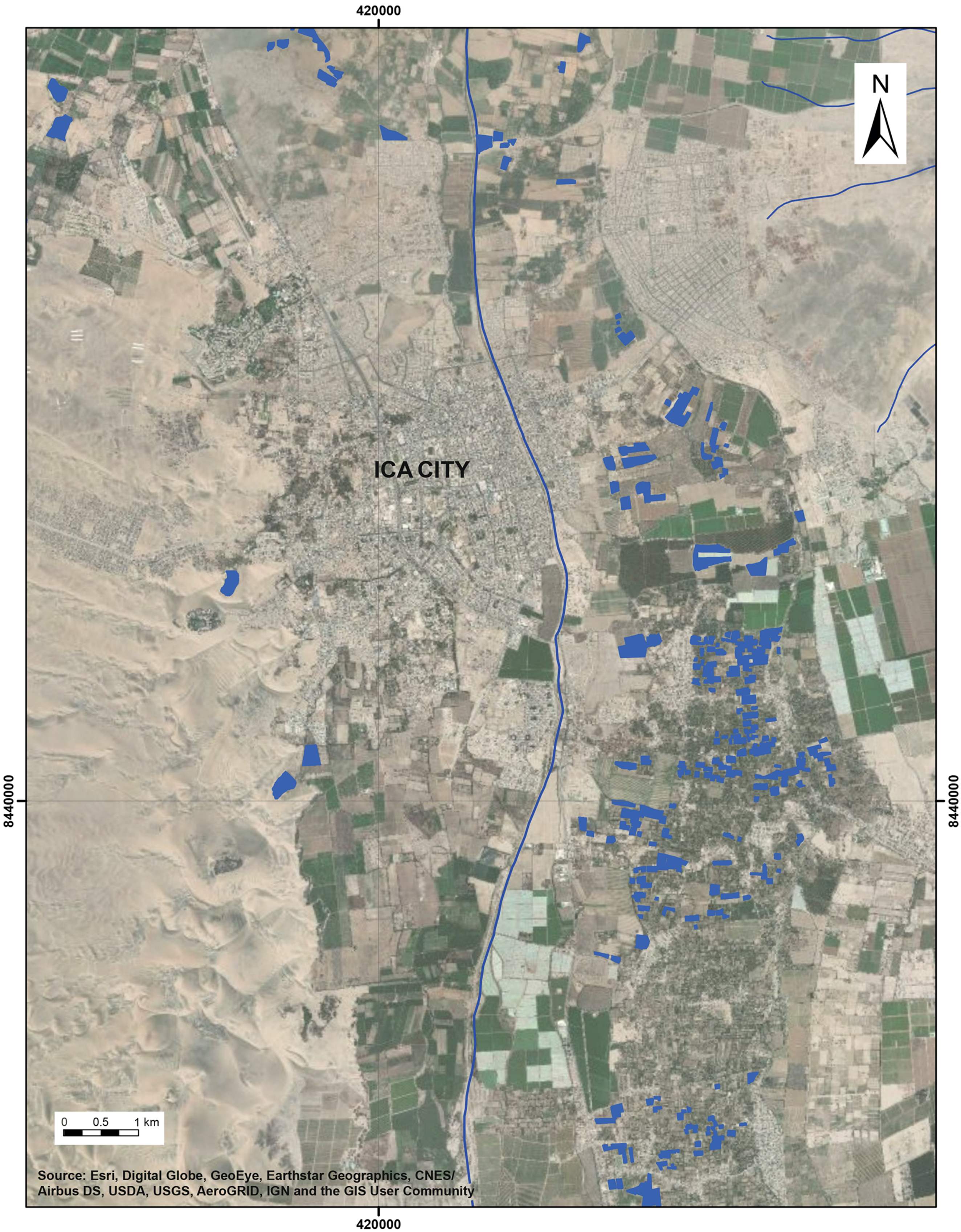

Fig. 7 Distribution of infiltration ponds (*pozas*) in the Ica Valley in 2016 (JUASVI 2016) [total pond area in blue (70 ha) in Pueblo Nuevo and Los Aquijes districts]

Fig. 8 Infiltration ponds in the Ica area: **a** full and **b** empty

a surface canal and produced an infiltrated volume of just over 0.2 Mm^3, but by 2016 there was about 23 ha of ponds in Los Molinos District (Fig. 7). In 2016 the number of ponds had dramatically increased to 660, mostly on privately owned land. These were concentrated along the Macacona Canal, which received water from the Ica River by gravity through a feeder. In this part of the Pampa Villacuri Aquifer there is little presence of evaporitic material in the soil that might induce salinisation of recharge waters, and render MAR through infiltration ponds hazardous. Annual cleaning and maintenance of both canals and ponds is essential to achieve effective groundwater resource augmentation. JUASVI is covering the operational cost of canal maintenance, which has amounted to about US$ 42,000 in the last 3 years.

More effort also needs to be put on refinement of the design of infiltration ponds. The most stable side-slope is 2/1 and the bottom of ponds should be carved with furrows to increase infiltration rates, to favour preferential sedimentation and to facilitate cleaning. Until the present, the selection of infiltration pond sites has been opportunistic, but geophysical surveying of the deep profile can aid site selection. According to available data, the average pond infiltration rate in the Ica Valley for the 2017 recharge cycle (123 days from 2 January to 4 May) was 6,000 L/m^2 (or 48 mm/day), which is more than 7 times lower than the 4-day infiltration test (360 mm/day). This is attributed to the longer duration of infiltration and likelihood that the field data include poorly located ponds. The level of success of recharge augmentation will in effect determine the degree to which demand management measures (mainly reducing the groundwater irrigated area) need to be applied to irrigation waterwell users in the long-term.

Demand-side management

The foundation of the national water resources agency ANA (Agência Nacional del Águas) in 2009 by the Peruvian Water Resource Law (Ley de Recursos Hídricos), together with regional offices (ALAs) and irrigation groundwater-user associations (JUASs), potentially provided a focus for resource conservation in water-stressed areas. ANA have passed various legal resolutions to prohibit new waterwell drilling and for assigning new groundwater rights in the Ica Valley and Pampa Villacurí. In the Ica area, ANA reinforced the waterwell drilling ban in 2012 and required formal certificates for all licensed waterwells, and used drones to ensure that no new drilling was occurring. However, the level of funding and personnel allocated to this urgent task subsequently declined, and this has frequently called into question the effectiveness of resource management by both national and local government agencies.

It is essential to make a clear distinction between the nature of the groundwater resources of the Ica Valley Aquifer compared to that of the neighbouring Pampa Villacurl. In the latter area much of the available groundwater represents a nonrenewable reserve (recharged in previous episodes of wetter climate) with only a modest subsurface inflow from the Ica Valley and the possibility of other very occasional recharge from any local flash-flows. Thus, extension of sustainable groundwater irrigation (beyond a very modest area) is dependent upon the transfer of surface water from the Ica and/or Pisco valleys and its use to artificially recharge the Pampa Villacurí Aquifer. The alternative is progressive depletion and abandonment of waterwells, and this may not be all that orderly since the aquifer is threatened by patchy up-coning of saline water from below, which could further reduce its useful life. However, this evolution does not threaten pre-existing settlers, because none existed.

On the other hand, the alluvial aquifer of the Lower Ica Valley has large freshwater storage reserves to buffer drought impacts, and permit adaptation to climate and economic change. It receives most of its recharge directly or indirectly from the Ica River, and the big change that occurred with the arrival of intensive cultivation practices (which are clearly much more water productive in terms of USS per m^3/ha) has been the replacement of spate irrigation and land flooding by drip irrigation with liquid fertilisation, greatly increasing the consumptive use (as opposed to abstraction) of groundwater. Clearly groundwater in the Lower Ica Valley will always be vulnerable to serious flow reductions in the Ica River due to upstream diversion—but this aside, the basis for management must be long-term sustainability, using the storage to balance between high and low river-flow years, with periodic revision (and much improved metering) of licensed abstraction rates to bring them into line with available recharge.

Integrating management for groundwater sustainability

Integrated water-resource management in the Ica Valley must embrace on the one hand the combination of several primary canals to divert flow from the Ica River, sedimentation structures, secondary canals and infiltration ponds (Fig. 9), and on the other hand improved licensing and metering of existing waterwells, the closure of illegal waterwells and some significant reduction in the land area cultivated.

The new Ica Water Resource Conservation Plan needs to be disseminated and understood, requiring the organization of focused workshops to agricultural irrigators and the population in general. In addition to raising awareness of the limits on sustainable groundwater resources, the workshops should discuss the techniques and costs of supply-side management and measures to improve water and energy use efficiency on farms.

The goal of the plan is sustainable groundwater resource exploitation with the level of abstraction set at the estimated current recharge of the system. The path from groundwater mining to safe yield must be pursued by means of indicators on:

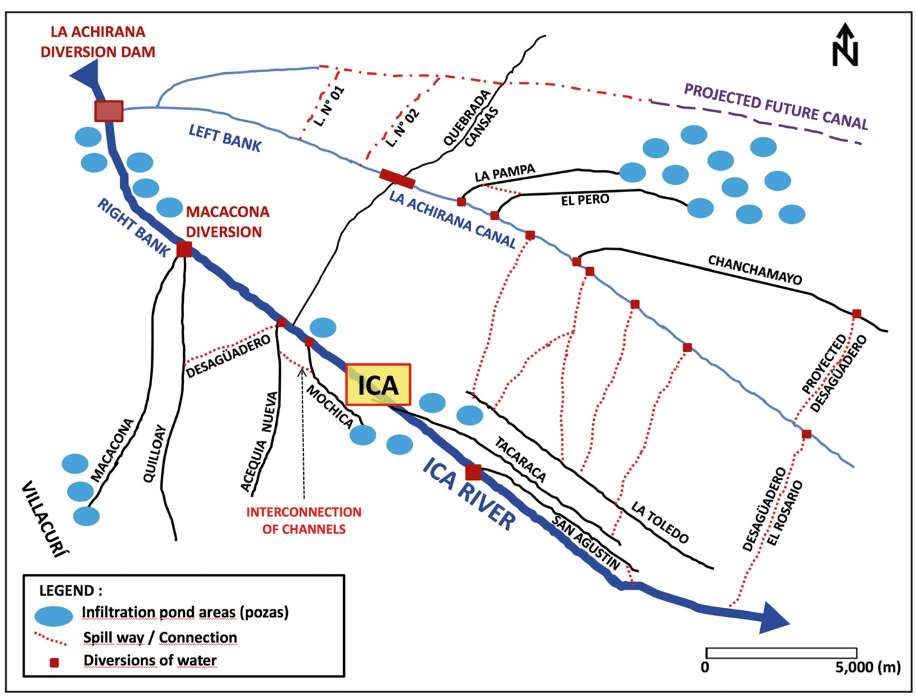

Fig. 9 Sketch map of canal diversions and infiltration pond zones in the Ica Valley (modified after Navarro 2015)

- Ratio between recharge volume and discharge volume for each subbasin or its manifestation in terms of water-table trends
- Annual evolution of the irrigated area with groundwater determined each January
- Annual evolution of the number of waterwells in operation by sub-basin
- Trends in the concentration of waterwell salinity
- Annual evolution of the number of waterwells closed because they do not have a license per year and of the number of new licenses granted
- Annual evolution of the frontier of irrigated agriculture

In view of the threat of greater irregularity in Ica River flow as a consequence of climate change, water resource management must be based on storing as much river water as possible during the rainy season, by forcing its infiltration through artificial recharge techniques. The overexploitation of the Ica aquifers is estimated to be 52 Mm^3/a, with river flow to the ocean being estimated at 115 Mm^3/a (in 2017, a wet year), but a large land area would be required as infiltration ponds to affect the required recharge.

Possible supplementary or alternative measures

The analysis for alternative water resources for the Ica area has identified a number of possibilities that are being, or might be, pursued:

- Capture of the Casablanca Springs (125 L/s), currently part flowing to the ocean for artificial recharge, which is still pending legal decision (Fernández 2019)
- Use of waterwells for artificial recharge, requiring a much smaller land area than infiltration ponds and offering potential of about 0.15 Mm3/a/waterwell over 120 days, but will require large-diameter (350+ mm) and innovation to avoid clogging
- Limit the depth of waterwell pump settings to physically constrain abstraction
- Increase the water-carrying capacity of the Macacona, La Libertad, Quilloay and Acequia Nueva canals to provide greater flow to the Pampa Villacuri Aquifer

Concluding remarks

The experience of the Ica area clearly demonstrates the enormous economic potential of irrigated agriculture where adequate groundwater resources are available; however, it also reveals the need for detailed adaptive groundwater use and land management, based on continuous appraisal of consumptive irrigation use and effectiveness of recharge enhancement measures, to avoid heavy aquifer overexploitation with serious socioeconomic consequences. Integrated and adaptive management measures such as these will not be successful without proactive dissemination and awareness-raising. It will be essential for the population in general to understand the factors determining the sustainability of their groundwater resources.

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