Interbasin water transfers at the US–Mexico border city of Nogales, Sonora: implications for aquifers and water security

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Nogales, Sonora, on the US–Mexico border, employs interbasin water and wastewater transfers to address water scarcity in the context of a rising population, a warming climate, and cross-border institutional asymmetries. A unique feature of its geography and border context is Nogales’s export of wastewater both north to the US and, starting with the August 2012 commissioning of a strategically positioned wastewater treatment plant, south to the Alisos basin, which is its principal drinking-water source. Thus, when the new plant is fully operational, it will result in indirect potable reuse of effluent via recharge of the source-water aquifer. This paper finds that such strategies contribute to increased water scarcity in Nogales, and to detrimental health, livelihood and environmental impacts in the source basin, thus raising questions about interbasin transfers as a principal water management strategy.

Keywords: interbasin transfer; water security; transboundary water resources; effluent; indirect potable reuse

Introduction

With global trends of population growth, urbanization and climate change, water is becoming increasingly difficult to procure in sufficient supply and quality to meet urban demand, which in many contexts is the highest water-policy priority (Molle, 2007). Particularly in arid and semi-arid regions, municipal water providers face an ever-growing challenge to locate sufficient water resources. The “hard path” approach to providing water is one that employs major infrastructure projects to pump, store and convey water to the sites of greatest demand (Gleick, 2003) and greatest political power. This approach can be limited to those who have the funds to construct and maintain such costly operations, so these projects tend to be authorized by central governments and serve major cities (Scott & Pineda Pablos, 2011). The hard path is consistent with a supply-driven approach to meeting water needs, in contrast to the “soft path”, which seeks to increase water efficiency and manage demand. Smaller cities find it difficult to mobilize the resources necessary to pursue hard path approaches, but Nogales has done so – perhaps without adequate attention to a broader set of water management options.

Interbasin transfers are often detrimental to rural communities in the source areas where the transferred water is extracted. When surface-water diversions or pumping of deep wells results in overdraft of the water source, the hydrological imbalance can displace the livelihood activities of local residents or, in extreme cases, the people themselves. In many areas of Mexico, water is a limited resource, either due to a semi-arid climate, such as in Nogales, or an exceedingly large demand, such as the case of Mexico

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City. The Metropolitan Area of the Valley of Mexico receives 31.5% of its water from external sources such as the Cutzamala River and Lerma-Balsas River basins and 66.4% of its water from local wells (Tortajada, 2006). The over-exploitation of the aquifer has caused widespread subsidence locally and adverse impacts elsewhere in the State of Mexico. For this reason, the government of the State of Mexico sued the government of Mexico City for USD2.2 billion for damages caused by the overdraft of the aquifers, though charges were later dropped with a change in government (Tortajada, 2006). The interbasin transfers, too, have caused social conflict and degradation of the soil in the Lerma Valley, largely ignored by the government, whose primary concern was to supply water to Mexico City (Tortajada, 2006; Tortajada & Castelán, 2003). Analogous to the case of Mexico City although at a far smaller scale, Nogales, Sonora, has pursued interbasin transfers primarily as a strategy to supply water and manage wastewater within its service area. Little attention has been paid to the environmental and social impacts in the source basin of Nogales’s interbasin transfer, which forms the majority of the city’s water supply.

Situated at the US–Mexico border, Nogales, Sonora (Figure 1), population 220,000 (INEGI, 2010), has for decades supplemented its drinking water supply with external aquifers and sent its wastewater downhill towards Rio Rico, Arizona, for treatment in the Nogales International Wastewater Treatment Plant (NIWTP). Starting 31 August 2012, however, Nogales began pumping a portion of its wastewater uphill to the south, in a second interbasin transfer, in an effort to conserve its effluent resource (Milman & Scott, 2010) within Mexico and to reduce the fees paid to the United States for wastewater treatment at the NIWTP (Sonora SI, 2011).

![Los Alisos and Upper Santa Cruz Basins](image.png)

Figure 1. The Los Alisos and Upper Santa Cruz Basins along the US–Mexico (Arizona–Sonora) border. The Upper Santa Cruz basin is transboundary, as is the Santa Cruz River, which crosses the international border twice.
In the form of interbasin transfers, Nogales, Sonora has enlarged its hydrologic sphere to encompass the Los Alisos basin. While interbasin transfers are enabling improved water service to Nogales city residents, some populations within the Los Alisos basin are marginalized in the process, because this previously self-contained community is now exporting its clean water and receiving Nogales’s wastewater in return.

The double interbasin transfer makes the Nogales case unique in that the new destination of the city’s pumped wastewater is the same location as Nogales’s principal source of freshwater, the town of Cíbuta, Sonora, in the Los Alisos basin. This creates a double interbasin transfer of water, in opposing directions, and results in indirect potable use of wastewater (via effluent recharge of the source water). In this manner, Nogales has created an artificial upstream–downstream relationship with Cíbuta, since Nogales may now use its ‘upstream’ position to take the majority of the freshwater and release contaminated water ‘downstream’ to Cíbuta, despite the natural elevation divide which had previously prevented this type of relationship.

This paper focuses on interbasin water transfers and their impacts on the water security of both the major border city of Nogales, Sonora, and the source basin community of Cíbuta. We use the definition of water security offered by Norman et al. (2010): “sustainable access, on a watershed basis, to adequate quantities of water of acceptable quality to ensure human and ecosystem health”. Both human and ecosystem health are considered in this study, for both of the basins involved in Nogales–Los Alisos water transfers. Although interbasin transfers are common around the world (Alagh, Pangare & Gujja, 2007; Carvalho & Magrini, 2006; Gupta & Van der Zaag, 2007; Howe & Goemans, 2003; Saurí & Del Moral Ituarte, 2001), little attention is given in the planning process and in subsequent studies to their effects in the source basin (the hydrological basin from which the water originates). This unique case of the inversion of the upstream–downstream relationship, as artificially constructed by the hard path approach to water resources management, has permitted us to frame and address in this paper the following research question: To what extent do the interbasin transfers between Cíbuta and Nogales resolve water scarcity concerns, and with what social, hydrological and ecological impacts on the source basin?

Methods and results

As a geographical analysis encompassing human and environmental interactions through time, this case study has required different methods to address each component. To evaluate the interbasin water transfers’ impact on water security in both basins, our methods included the following, with brief mention here of the objectives: (a) interviews with key informants to determine present water availability; (b) remote sensing analysis to link past ecological trends (especially of riparian vegetation) with changes in the hydrological regime resulting from water transfers; and (c) a basic estimation and projection of the hydraulic balance for both source and demand basins to assess future water security scenarios. Interviews with ranchers in the source basin provided insight on both social and hydrological impacts of interbasin transfers via accounts of decreasing surface and well water. Interviews with water managers provided perspective on both strategic infrastructure plans and the supply and demand trends of the municipal water. Remote sensing vegetation change indices were evaluated to determine the ecological impacts of transfers of groundwater that is linked, via shallow groundwater, to surface flows in the riparian corridor. Satellite scenes enabled glimpses into the past which served as proxies for historical water records. Last, hydraulic balance projections clarified the
extent of present and future water displacement resulting from interbasin transfers, as calculated using varying scenarios of aquifer recharge and population growth. Together, these techniques form a more complete view of the interbasin transfer challenge, which is of increasing global importance. Internationally, cities are growing and per capita water use is rising, so the urban demand is greater even as in many cases the supply dwindles or becomes contaminated. To meet this demand, the supply must come from farther – either deeper, in the case of some groundwater sources, or farther afield, such as surrounding basins. When these costly transfers occur, they inherently disrupt natural flows and can have significant impacts on communities and ecosystems dependent on those water sources.

To assess these impacts, we have used mixed methods including interviews, remote sensing, and a hydraulic balance analysis of the basins involved. We report here the methods and results of each component of the study, beginning with the interviews, which we then relate to remote sensing–based assessment of ecological condition. Finally, we assess the hydraulic balance resulting from the interbasin transfers with their implications for human and ecological communities in the source basin.

**Interviews**

Interviews were conducted to provide background, context, and subjective accounts of the water supply, both from an urban water manager’s perspective and from that of ranchers in the source basin who have been directly affected by the transfers. In the absence of hydrological data such as river and well levels in the area, interviews provided crucial information on the impact that the interbasin transfers have had upon the surrounding areas. Preliminary interviews, in which ranchers reported the deaths of hundreds of fruit trees in response to aquifer drawdown around a municipal well, prompted the choice of a remote sensing study to assess vegetation change along the Los Alisos riverbed to see whether this phenomenon occurred throughout the Los Alisos well field. Other preliminary interviews revealed the unsustainability of the groundwater extraction via accounts of dried-up wells and the disappearance of the Los Alisos River since municipal pumping began in the summer of 1996; this information provided the impetus for the hydraulic balance study to evaluate the degree to which the outflow exceeds the inflow.¹

Ten residents of Cíbuta and Nogales were interviewed, including ranchers, common-pool landholders, and urban residents. A further 10 water service professionals in Nogales, Sonora, were interviewed, ranging from site managers of the new Los Alisos wastewater treatment plant to managers, technicians and planners at the municipal water service provider of Nogales (Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento, or OOMAPAS). All interviews were conducted in Spanish and recorded for accuracy. Water professionals were selected for interview based on their specialized knowledge and were interviewed individually, while residential participants were often interviewed as families and were selected based on the snowball method, in which interviewees suggested other participants who might be able to contribute to the study.

When asked about the interbasin water transfer in the Los Alisos basin, residents’ opinions varied, depending on their relationship with OOMAPAS. Those on communally owned (ejido) land had agreed to allow the drilling of two municipal wells on their property in exchange for free access to piped domestic water, which, they say, has never failed them. The majority of Cíbuta residents, however, have no such agreement with OOMAPAS – indeed, some wells were drilled on private property without legal permits. Town residents must not only pay for the municipal water, but they have had to abandon
their private wells, which have, in large part, run dry since high-powered municipal wells in the area have lowered the water table.

Two families of ranchers expressed fears of losing their land holdings because their wells and reservoirs are drying and they cannot afford gasoline to pump water for irrigation. They may consequently lose their cattle, unless rain refills their reservoirs, which had been fed by surface springs before the drop in the water table. One family said that within six months of the installation of a nearby municipal well, their well level dropped by six metres, requiring them to pay to operate the pump in their deepest well in order to have enough water for their cattle. They stated that despite numerous droughts, never before had the water dropped so severely in their 74 years of ranching. They feel they have not been compensated for this infraction on their property and water rights. This type of interaction has been seen throughout Sonora, where urban water management choices have jeopardized traditional agricultural and livestock livelihoods (Díaz-Caravantes & Sánchez-Flores, 2011). Despite water-management centralization in Mexico (Scott & Banister, 2008), some city governments have attempted to play a proactive role in the implementation of interbasin transfers. For example, in north-eastern Mexico, farmers downstream of the city of Monterrey’s diversion of the Río San Juan were compensated both financially for unirrigable land and hydrologically in the form of effluent allocations to use for irrigation (Scott, Flores-López & Gastélum, 2007). In Cíbuta, one vocal family of ranchers had made public complaints in the newspaper and over the radio about their loss of livelihood from the municipal groundwater extraction, but they did not receive or expect any compensation from the municipal water company.

Nogales water managers at OOMAPAS, on the receiving end of the transfer, did not feel that Cíbuta was affected and were instead concerned about the welfare of the city of Nogales. They felt that their infrastructure was out of date and could not keep up with the rise in demand. Figure 2 shows Nogales’s stark rise in population, which is due in large part to urban migration, or the movement of workers from rural areas to urban areas, generally in transition from the agricultural sector to the industrial or commercial sector.

The water demand has risen not only because of population growth but also for extensive industrial use, such as in the 95 active factories (as of 2006) in Nogales (Wilder, Scott, Pineda-Pablos, Varady & Garfin, 2012).

The result of this city-ward migration is that there are too many water users for the limited supply. Only 39% of Nogales residents benefit from a 24-hour water connection in their homes (Gómez & Salas, 2003). Although water managers say they do not have a long-term sustainable supply plan, they are hopeful that repairs of leaky pipes and initiatives to promote water conservation will prove effective in increasing efficiency of water use. For instance, OOMAPAS implemented metering of domestic water in many parts of Nogales in 2010, and in one year’s time they saw dramatic reductions in consumption as a result.

Part of the income generated by the water metering goes toward the construction and operation of the new wastewater treatment plant in Los Alisos. The purpose of this plant, according to managers, is to treat a portion of the city’s wastewater and thus relieve the burden on the NIWTP, which on average has been treating an excess volume of Mexican wastewater: 126% over the volume authorized by binational accords between Mexico and the United States (434 litres per second, or lps) (IBWC, 1988; NADB, 2012). Other benefits of this plant, they say, include providing first-time sewerage to over ten thousand citizens, as well as supplying recharge to the over-exploited aquifer using effluent from the treatment plant, which is just upstream of the majority of the wells in the Los Alisos municipal well field (La Prensa Sonora- Arizona, 2012). When asked for details, however, project managers had no clear answers on the amount of recharge that would take place. There was no plan to construct infiltration basins to maximize recharge; the plan, they said, is for the effluent to flow downstream in the Los Alisos River bed.

Residents of Cibuta are hopeful that the return flow of the effluent will bring life back to the river that once flowed through the town, but they have misgivings about the water’s quality. In 2010, several children were reported by local residents to have serious illnesses that were traced to the river, which flows ephemerally after rainstorms. The illnesses, including hepatitis, were attributed to contamination from a jail located a few kilometres upstream, whose sewage flowed into the riverbed, sickening or killing animals that drank from it. Another upstream source of contamination is the new housing development, Fraccionamiento La Mesa, a government low-income housing area of about 5000 homes constructed in the Los Alisos basin to accommodate the growing population of Nogales. The wastewater treatment plant for this community is inadequate because according to water managers, it was only designed to treat about half of the 30 lps of wastewater produced. Residents fear that the Los Alisos wastewater treatment plant, which receives about 10 times the volume of wastewater that is produced in Fraccionamiento La Mesa, would have serious negative impacts on the health of all downstream, including wildlife, if it should let untreated water flow downstream in the same way that Fraccionamiento La Mesa does.

In summary, the exploitation of the Los Alisos aquifer by OOMAPAS has lowered the water table in Cibuta, as evidenced by the disappearance of the Los Alisos River and the drying of personal wells throughout the town of Cibuta since the onset of large-scale pumping in the Los Alisos well field. The drop in the water table has harmed the livelihoods of several residents, especially ranchers, who depended on their wells to irrigate their pastures and give water to their cattle, and they feel uncompensated for this loss. The southward expansion of the city of Nogales has caused the contamination of the Los Alisos River upstream of Cibuta due to the introduction of untreated wastewater from Fraccionamiento La Mesa and other sources, provoking illness in Cibuta. While the Los Alisos treatment plant may prove beneficial by raising the water table, it also presents a
potential hazard to water quality if there are flaws, accidents or excess volumes of wastewater pumped to the treatment plant – which could then have impacts reaching Nogales, since the municipal well field is in the same stretch of the riverbed as the treatment plant.

Remote sensing: riparian vegetation change in the interbasin transfer source basin of Los Alisos

Residents of Cibuta have reported major negative impacts on the ecosystem since municipal pumping began about 15 years ago. In response to the eyewitness accounts of the drying river, wells and trees, we sought records of historic well levels in the area to verify and quantify the drop in the water table. Unfortunately, those records were unavailable, so in this study we have used riparian vegetation health along the banks of the Los Alisos River as a proxy for groundwater level around the well field (Elmore, Mustard, Manning & Lobell, 2000), since the health and abundance of the riparian vegetation in periods of little or no precipitation is associated with the height of the water table (Johnson, Dixon, Simons, Jenson & Larson, 1995). We performed a remote-sensing analysis of the riparian vegetation change along Cibuta’s well field since 1996 to see whether the drawdown of groundwater showed significant impact on local vegetation and represented an unsustainable decline within the basin of the now-ephemeral Los Alisos River.

Methods include Normalized Difference Vegetation Index (NDVI) and image differencing to analyze the riparian vegetation changes in Landsat images from 4 May 1996 to 28 April 2011. If the NDVI image showed a decline in riparian vegetation after the extensive groundwater extraction from the well field along the river, this analysis would corroborate the claims of the interviewed residents of Cibuta, who stated that the municipal pumping had negative ecological impacts in the area. According to OOMAPAS-Nogales, the pumping in Los Alisos began in 1996, and the most recent well began pumping in July 2010. The choice of this time span was made to capture any changes in vegetation that might be a result of municipal pumping of the groundwater in the Los Alisos basin. The subset of the Landsat 5 image is based on the location of the Los Alisos well field, which includes the town of Cibuta and the Los Alisos River. Anniversary dates for the images are in late April/early May, which precede the summer monsoon season and follow a long period without rain (Figure 3). Therefore, vegetation health at this time of year reflects the supply of groundwater rather than the amount of precipitation. The targeted riparian species are those that are not desert adapted. Drought-sensitive riparian vegetation is a more sensitive indicator of water loss than mesquite trees, for example, which can survive under drier conditions (Stromberg, Tiller & Richter, 1996). The selected years, 1996 and 2011, had similar precipitation, patterns showing little spring rainfall. The greatest amount of vegetation change took place along the Los Alisos River, although the type of change varied. Around the town of Cibuta, there was an increase in vegetation (which residents say, may be attributed to intentional planting), but downstream, there was a decrease in the natural riparian vegetation along the riverbed.

Overall, the image difference of this NDVI subset does not show significant change along the riparian corridor for this time period. Additional change detections of different time frames corroborate the reports of dead or dying oak trees in the hills, but riparian vegetation has a similar amount of greening and dieback. It is known, however, that the wells have been pumped steadily and that the water table is dropping. Since reduction of riparian vegetation is an expected outcome of groundwater decline (Jin, Schaepman,
Clevers, Su & Hu, 2011), our hypothesis was that the resultant image from the NDVI change detection of the 1996 and 2011 riparian area downstream of the well fields would demonstrate this decrease in riparian health and vegetation productivity; but since there was little change, it appears that either the riparian vegetation is drought resistant, or the water table is still within reach of the vegetation’s roots. The remote-sensing vegetation analysis showed great ecological impact resulting from the decade of drought in the study period, but did not reveal a strong decline in vegetation due to interbasin transfer in the riparian area downstream of the Los Alisos well field.

**Hydraulic balance of source and destination basins**

To quantitatively estimate the impacts of Nogales’s interbasin transfers, we conducted simple hydraulic balance studies on both the Sonoran Upper Santa Cruz basin and the Los Alisos basin for three time periods. The objective was to estimate how the inflow compares (and will compare) to the outflow, and thus to gauge the stability of the aquifer and the city’s freshwater supply. In 2009, Mexico’s National Water Commission conducted in-depth studies of aquifer water balances, including precipitation, infiltration, storm water and sub-surface flows (CONAGUA, 2011), so our methodology focuses on the current and projected hydraulic balances of the two basins. Also, the CONAGUA report shows an 11 million m³ surplus of water for the Los Alisos basin in 2009, which contradicts observations from water professionals that the water table has been consistently dropping, as seen in the Los Alisos well field (personal communication, OOMAPAS, November 2011). The reported surplus of water in CONAGUA’s water balance is probably related to the omission of significant extractions by untitled wells. Several of the high-productivity municipal wells in Los Alisos well field are currently untitled (personal communication, OOMAPAS, November 2011).

The city of Nogales overlies the Nogales Wash aquifer and the transboundary Santa Cruz aquifer, both of which lie in the Upper Santa Cruz basin (Figure 1).
municipal purposes comes mostly from three sources: the Mascareñas well field along the Sonoran Santa Cruz River to the east; multiple small wells throughout the city centre; and the Los Alisos well field. Of the three sources, only Los Alisos must be pumped over an elevation divide to supply the city. For this reason, we have only included the water transfer from Los Alisos in the calculation, since water originating in the Sonoran Santa Cruz basin either remains in that basin (for outdoor use) or goes down the drain and enters the sewage system, which currently is included in the measured volume of water moving across the border toward the NIWTP in Rio Rico, Arizona. In this study of interbasin transfers, we have only included quantities of water that terminated in basins other than where they originated.

The Sonoran Santa Cruz sub-basin has a net loss of about 8.8 million cubic metres (mcm) of water per year. This number is based on the 2011 water transfers, which included an average 270 lps inflow from the Los Alisos basin and a 548 lps outflow to the NIWTP (Table 1) (personal communication, OOMAPAS, June 13, 2011). This annual loss of water due to transfers to the United States is not indicative of sustainable water management practice. According to a study by Morehouse et al. (2000), Mexican water officials have stated that by 2015, Nogales would require an additional 11,750 acre-feet of water per year (14.5 mcm/y) to sustain its population, a quantity equal to 63.5% of the annual volume of municipal water used (Diaz & Morehouse, 2003).

This water deficit in Nogales, Sonora, will go from bad to worse in coming years. Six neighbourhoods in the south of Nogales, with a combined estimated population of 34,560, will soon be connected to the wastewater collection system for the first time (EPA, 2008), which means improved sanitation conditions, but less return flow to the Sonoran Santa Cruz basin. The wastewater generated in this area, which has historically remained in the basin in the form of cesspools and septic systems (EPA, 2008), will be sent over the nearby elevation divide to be treated and released as effluent in the Los Alisos basin. Once this is implemented, probably in early 2013 (personal communication, OOMAPAS engineering supervisor, 13 June 2011), there will be about a 22% increase in the wastewater leaving the Sonoran Santa Cruz basin. The hydraulic balance calculations presented here are based on the assumption that this project will be implemented in full on the timeline stated by the interviewed engineer.

We can project for 2015 a 705 lps wastewater discharge from the city of Nogales, to be distributed between the two wastewater treatment plants leaving the Sonoran Santa Cruz sub-basin (Table 1), based on a 22% increase in wastewater produced from the six neighbourhoods on top of an additional 30,480 people living in the area. This increased population is extrapolated from the 13.8% population rise between the 2005 interim census and the 2010 National Census (INEGI, 2005, 2010). As for inflow, the actual amount of water that will be pumped from the Los Alisos well field is unknown since it is dependent on climatic factors, unknown amounts of recharge from the new effluent resource, and potential new decisions on municipal pumping. One OOMAPAS water manager stated that the current plan is not to drill additional wells but to improve efficiency in the system by repairing leaks and increasing water metering to encourage conservation. Assuming there will be no additional wells, we can infer that the productivity of the Los Alisos well field will continue its downward trend. An OOMAPAS engineer with 13 years of experience working on the Los Alisos well field stated that the production of the wells has declined by about 30% since their original installation.

Residents in the Los Alisos basin have also witnessed drops in the water table. Many municipal wells are on private property, and landowners reported that technicians have come to deepen the wells since initial installation. The residents and engineers estimated
Table 1. Projected hydraulic balance of the Sonoran Santa Cruz basin, 2011, 2015 and 2020 (flow rates in litres per second). Inflow is dependent on the productivity of the Los Alisos well field. The net loss of water from this sub-basin begins at 278 lps in 2011 to a maximum potential loss of 601 lps in 2020. Despite an effort to increase well productivity in the Los Alisos basin, which depends on the recharge capacity of the effluent from the Los Alisos treatment plant, the Sonoran Santa Cruz basin has a growing net loss of water due to its export of wastewater to the United States and to the Los Alisos basin.

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<td>Inflow (100% recharge)</td>
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* The permissible limit is 434 lps of wastewater to send to Rio Rico, so in 2011, OOMAPAS paid high rates for treatment of the additional 114 lps (average) of wastewater sent to the NIWTP.

** OOMAPAS plans to continue sending 434 lps to the NIWTP (Rio Rico) and send the overage to Los Alisos.

*** The Los Alisos plant’s maximum capacity is 330 lps, and it receives 30 lps from Fraccionamiento La Mesa. It is unknown whether the excess 69 lps will be sent to Rio Rico or Los Alisos.
that the municipal wells were 80–100 metres deep. In view of the 20-metre depth of the private wells that previously served the ranchers, the fact that it was necessary to deepen an 80-metre well on the same property indicates a severe drop in the water table.

In order to calculate the hydraulic balance using the 30% decline estimated by OOMAPAS from 1996 to 2011 (a 15-year period), we can infer a 9 lps drop in production each year. Since the average production of the well field between 2008 and 2011 has been 315 lps (personal communication, OOMAPAS, 13 June 2011), that would suggest that the original production was 450 lps before the 30% drop: \( \frac{450 \times 0.3}{15} = 9 \text{ lps for every year since 1996.} \) It should be stressed that this represents a historical average over 15 years; any future changes would be subject to a range of processes including recharge influenced by surface flow events, climatic change and other uncertain factors. With no additional input, this yields a total estimated outflow of 279 lps from Los Alisos in 2015 and 234 lps in 2020. Of this outflow, however, 32 lps will go to Fraccionamiento La Mesa, so Nogales would receive 247 lps of water in 2015 and 202 lps in 2020 from Los Alisos (Table 2).

For wastewater projections, we must look into population projections. Using the same 13.8% rise in population that occurred between 2005 and 2010 (INEGI, 2010), we can project a 2015 population of 250,772 and a 2020 population of 285,468 residents in Nogales, Sonora. The corresponding rise in exported wastewater can be estimated as follows.

The six neighbourhoods represent 16% of the 2010 census population, and once they receive sewerage, the Nogales population served will rise from 70% to 86%. If 86% of the 2015 population (215,664) produces 705 lps of wastewater, then 86% of the 2020 population estimate will produce about 803 lps of wastewater.

**Potential effluent recharge of the groundwater beneath the Los Alisos well field**

The water supply coming from Los Alisos is likely to continue to decline as the water table continues to drop, though there is the hope that the return flow generated by the effluent from the Los Alisos treatment plant will recharge the aquifer to some extent, depending on (1) the amount of water which is treated there (to a maximum rate of 330 lps, the maximum capacity of the plant), and (2) the amount of effluent that percolates through the ground to the level of the aquifer.

The plan is to release 434 lps (the limit specified in the binational agreement) of municipal wastewater to the NIWTP in Arizona and the rest of the wastewater to the Los Alisos plant, which, in turn, will discharge all of its effluent into the Los Alisos River channel. This will allow the effluent to flow south through the neighbouring towns beyond the Los Alisos well field, which spans about 10 kilometres directly downstream of the treatment plant. We estimate that about 3% of the effluent will evaporate (based on pan evaporation data from Nogales, Arizona) and that another portion will flow further downstream rather than recharging the groundwater of the well field. Since the hydraulic gradient of the water table in general follows the slope of the surface, the water that percolates to recharge the aquifer south of the well field will be out of reach of the Los Alisos well field. We can, however, make well production estimates for the best-case (100% percolation of effluent just downstream of the plant) and worst-case (zero percolation) scenarios, knowing that the actual recharge will lie between these values. If there is 100% recharge of the additional effluent inflow, we can then increase the estimated well production, up to a maximum of 450 lps, or the estimated initial flow rate before the
Table 2. Projected hydraulic balance of the Los Alisos basin, 2011, 2015 and 2020 (flow rates in litres per second). Outflow is dependent upon the effluent recharge of the well field. The net water loss from this basin begins at 270 lps in 2011 to a potential gain of 98 lps in 2020 (with zero effluent recharge) or a potential loss of 118 lps with 100% effluent recharge. The greater the recharge of the well field, the more water will be pumped to the Sonoran Santa Cruz basin. If there is minimal recharge, the cones of depression will continue to deepen and the volume of water pumped from Los Alisos will decrease.

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* The maximum inflow for the Los Alisos treatment plant is 330 lps, of which 30 lps comes from Fraccionamiento La Mesa. La Mesa values come from personal interviews with OOMAPAS employees and do not include future projections.
water table was lowered from over-extraction. This uncertainty in aquifer recharge leads to the range of well productivity values found in Tables 1 and 2.

Discussion

The Los Alisos basin, from which about half of the city of Nogales’s municipal water originates, has shown severe signs of groundwater decline. The municipal well field is situated along the ephemeral Los Alisos stream in Cibuta, a town of 630 residents (Foro-Mexico, 2011). The majority of the water from the Los Alisos well field goes to Nogales, but about 32 lps goes to a major housing development, Fraccionamiento La Mesa (personal communication, OOMAPAS, 13 June 2011). Since La Mesa is in the Los Alisos basin, north (upstream) of Cibuta, this water is not considered an export from the Los Alisos basin. In 2011, the hydraulic balance of the Los Alisos basin shows a deficit of 270 lps, which has been felt by the local community, particularly the ranchers, who can no longer afford the pumping costs to provide water for their livestock, water which had hitherto flowed naturally from springs.

When the Los Alisos plant began treating wastewater from Nogales in 2012, it generated substantial return flow for the Los Alisos basin, which for over a decade had only been exporting water. A major factor in the Sonoran government’s decision to operate a treatment plant on Mexican soil was to avoid paying high rates for wastewater treatment at the NIWTP in Arizona in excess of the 434 lps permitted by US–Mexico official agreement. In addition to the quantity in excess of 434 lps, an estimated 113 lps of inflow to Los Alisos will come from the installation of wastewater services for the six neighbourhoods mentioned above, which will have sewage connections for the first time once the project is completed around 2013. The hydraulic balance estimates for 2015 include this additional inflow, and are shown in Table 2, where there is a column for the 100%-recharge scenario and another for the zero-recharge scenario. We can assume that the actual values will lie in between, but percolation will not be optimized because there are no plans for an infiltration basin to facilitate the recharge of the effluent near the well fields. Also, there is a risk of reduced infiltration due to biological factors. Experience on the Arizona side of the Santa Cruz basin, where effluent has long been released to natural channels, indicates that nitrogen and phosphorus may contribute to the formation of an algal mat that lines the stream channel and impedes infiltration over a distance of several miles downstream of the effluent release point. This biological factor could represent another impediment to infiltration and subsequent recharge.

For the 2020 estimate, the outflow of the Los Alisos well field under the zero-recharge scenario is again reduced according to the 9 lps/y estimated decline in well productivity (based on historical averages, as indicated above), and the maximum outflow is set at the initial pumping rate before over-extraction occurred, or 450 lps minus 32 lps for La Mesa. The wastewater produced by Nogales and La Mesa will at that point have exceeded the maximum capacity of the Los Alisos plant (330 lps), so in Table 1 the additional volume of wastewater is added to the side of the NIWTP in Arizona, for a total of 503 lps, which exceeds the 434 lps limit and is very near the average rate of flow to the NIWTP before the inauguration of the Los Alisos treatment plant. In other words, it will take an estimated eight years of operation before the additional capacity of the plant is utilized as a result of the city’s growth. Based on the projections in Table 2, the increased production of sewage will necessitate the construction and completion of the second stage of the plant (from its present 220 lps capacity to its maximum 330 lps capacity), possibly sooner than engineers anticipated. This estimate indicates that it will be necessary to complete the second stage
of the treatment plant construction before the year 2015, since 2015 shows 301 lps to be
treated in Los Alisos (271 lps from Nogales + 30 lps from La Mesa).

For a period of about eight years, the municipal water company will be able to avoid
paying additional fees at the Nogales International Wastewater Treatment Plant on the US
side of the border by staying within the 434 lps average permitted rate. In approximately
eight years, at current growth rates, total wastewater will have surpassed the combined
limits of both treatment plants. At that point, it is uncertain what will be done with the
excess wastewater, and its implications for contamination and public health are unknown.
If treatment capacity is not increased, then the choice must be made whether to overload
and contaminate the US side, resulting in higher costs for OOMAPAS, or to overload the
Los Alisos treatment plant, which would raise contamination on the Mexican side of the
border. OOMAPAS will then decide whether to exercise its natural upstream relationship
with Arizona or to exert its engineered upstream relationship with the rural peri-urban
community of Cibuta by pumping excess wastewater to an overloaded treatment plant in
the Los Alisos basin.

Conclusion
The objectives of this study were to evaluate the implications of the two-way interbasin
transfer (water supply and the reverse flow of wastewater) between Nogales and Los
Alisos in terms of the long-term water security of inhabitants of both basins, and to extract
lessons of broader relevance. Interviews with water managers reveal that they are, indeed,
concerned about Nogales’s future but do not have a long-term plan to ensure supply. With
limited funds, managers are relying on both water transfers and efficiency measures within
existing infrastructure to try to meet the demands of the residents and the industries they
support. Ranchers of Cibuta have been negatively impacted by the interbasin transfer
because the cones of depression surrounding the municipal wells have reduced or dried out
altogether the personal wells for their homes, the spring-fed reservoirs for their cattle, and
the Los Alisos River, which, according to residents, changed from perennial to ephemeral
shortly after major pumping began. Additionally, Cibuta residents have shown concern
about the new wastewater treatment plant just upstream of them, which was commissioned
on 31 August 2012. Though they are hopeful that the river may return, they fear
contamination, which has been a problem in the past as a result of other wastewater flows
from urban development on the Alisos side of the elevation divide.

Most interviewees of Cibuta spoke of reduced vegetation in the area over the last
decade – some reduction due to deforestation, some due to drought, and some due to fire.
We ran vegetation change analyses using NDVI of ‘before’ and ‘after’ satellite images of
the Los Alisos riparian area, but the changes in the image were not drastic and vegetation
health appeared to vary in different areas of the river. We concluded, upon a follow-up
interview, that the reported tree deaths were non-native fruit trees, and thus more
vulnerable to water shortage, but that the desert-adapted mesquite, alder, and near-riparian
oak trees had not suffered significantly up to that point.

Hydraulic balance considerations show that while both the Los Alisos and the Sonoran
Santa Cruz basins had a net water loss in 2011, the addition of large volumes of effluent to
the Los Alisos basin may bring the water balance to equilibrium, and could partly restore
ranching livelihoods and ecological habitats that were harmed by extensive pumping. It
has yet to be determined to what extent the influx of effluent will augment the potable
water available to Nogales via the Los Alisos well field, since much of the effluent is likely
to pass downstream along the river channel rather than percolating to the water table.
beneath the wells. The Sonoran part of the Upper Santa Cruz basin, however, will not have any additional return flow. In fact, higher volumes of water will be leaving the basin in the form of wastewater due to the increases in population and in sewerage service to existing residents, exacerbating the current water security problems.

This study has provided case evidence of urban growth in water-scarce conditions and the associated trade-offs in water management options. Economic factors worldwide are driving urban migration, but urbanization trends are at odds with sustainable natural resources management, because resource extraction and waste disposal are moving farther away from urban centres to accommodate demands for goods and services. Interbasin water transfers occur in cities with the financial and technological means to carry them out, with or without consultation or permission from residents of the source basin, whose health and safety can be affected. Particularly in northern Sonora, where a decade of drought is being followed by increased temperatures, (Christensen et al., 2007; Scott, Megdal, Oroz, Callegary, & Vandervoet, 2012), a long-term plan must be devised that will not only conserve the water resource but also share it in an equitable fashion with human and environmental needs.

Notes

1. Mexico’s National Water Commission reports an 11.26 mcm net gain in the water balance of the Los Alisos basin (CONAGUA, 2011), but some municipal extractions are unaccounted for in this balance, as described in a subsequent section of the paper.

2. The 22% increase is based on the following estimates: 70% of the 2010 population of 220,292 has sewerage, generating 504 lps of wastewater (EPA, 2008; INEGI, 2010; personal communication, OOMAPAS, 2011). If that seventy percent (154,204 people) creates on average 504 lps average of sewage, then 34,560 people (from the EPA estimate of the population of the six neighborhoods who will soon be connected to the sewage system) would produce 113 lps of wastewater, or a 22% increase in the 2010 number leaving the city).

3. Per minute 276 of the 1944 treaty as administered by the International Boundary and Water Commission, IBWC/CILA (IBWC, 1988).

References


