Location	Sonora State, Mexico
Contractor	Comision Nacional del Agua
Period	2004-2005

Introduction

Due to scarcity of surface water resources and closure of basins, over-extraction of groundwater is becoming the worldwide next water resources problem. Most aquifers are exploited at unsustainable rates. Good groundwater management plans based on balancing recharge and extractions are fundamental for making the use of this resource sustainable. Spatially distributed information on the extraction is of paramount importance. This crucial information can be obtained from SEBAL-based ET maps.

Table 1 reveals that Mexico is ranking 5th on the world scale of groundwater users. By Mexican law, the Gerencia de Aguas Subterraneas (GAS) of the Comision Nacional del Aqua (CNA) has to prepare groundwater management plans. These plans specify allowable extractions of all Mexican aquifers. One of the first steps for such program is the description of the extractions - both artificial through pumps and natural through deep rooting preatophytes and other types of natural vegetation.

This study was conducted together with dr. Jaime Garatuza-Payan (ITSON) and dr. Christopher Watts (UNISON)

Sonora State

Northwest Mexico is a region of highly variable topography. The peak elevation of Sonora is approximately 2400 meter AMSL. The majority of the elevations lay in the range between 200 and 900 meter AMSL. Above 500 m elevation, deciduous broadleaf forests and woody savannas are the dominant land use types.

Table 1. Groundwater use for agriculture (source: http://www.iah.org/briefings/GW%20Brief.pdf)

Rank	Country	Irrigated area *Mha*	Irrigation water use *km³/yr*	Proportion groundwater *%*	Groundwater use for irrigation Km³/yr
1	India	50.1	460	53	244
2	China	48.0	408	18	73
3	Pakistan	14.3	151	34	51
4	Iran	7.3	64	50	76
5	Mexico	5.4	61	27	16
6	Bangladesh	3.8	13	69	9
7	Argentina	1.6	19	25	5
8	Morocco	1.1	10	31	3

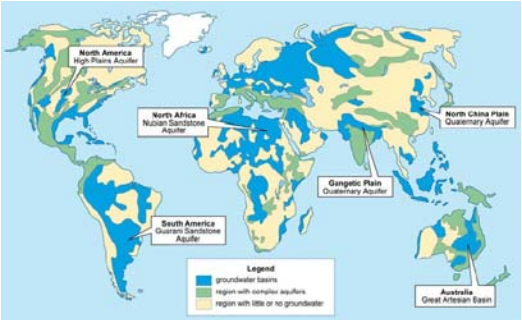
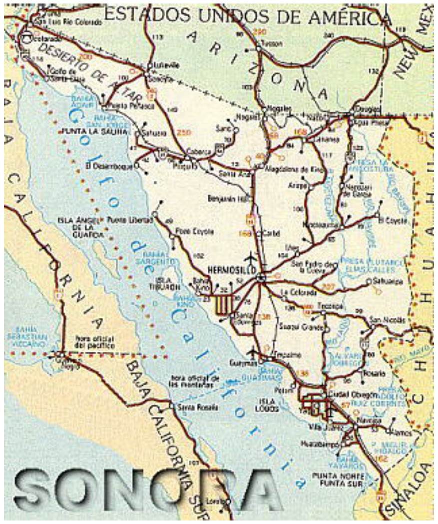


Fig. 1. Worldwide aquifer map (source: http://www.iah.org/briefings/GW%20Brief.pdf)



Pumping groundwater is like making constant withdrawals from a bank account without ever paying anything into it

Source BBC: (http://news.bbc.co.uk/hi/english/static/in_depth/world/2000/world_water_crisis/default.stm)

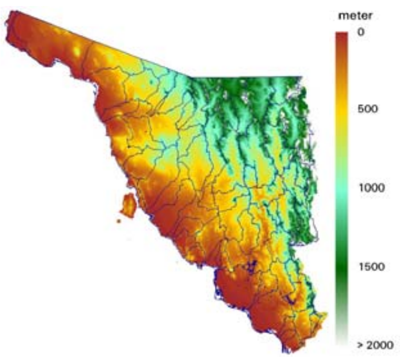


Fig. 2. Digital Elevation Model (source: USGS)

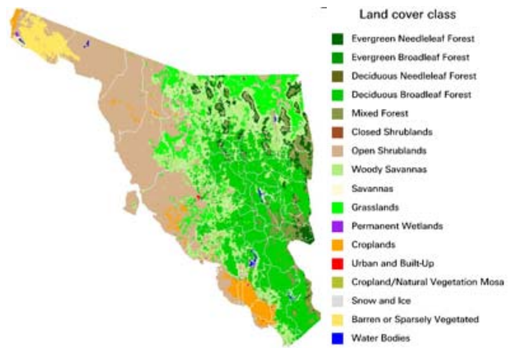


Fig. 3. Land use map (source: IGBP)

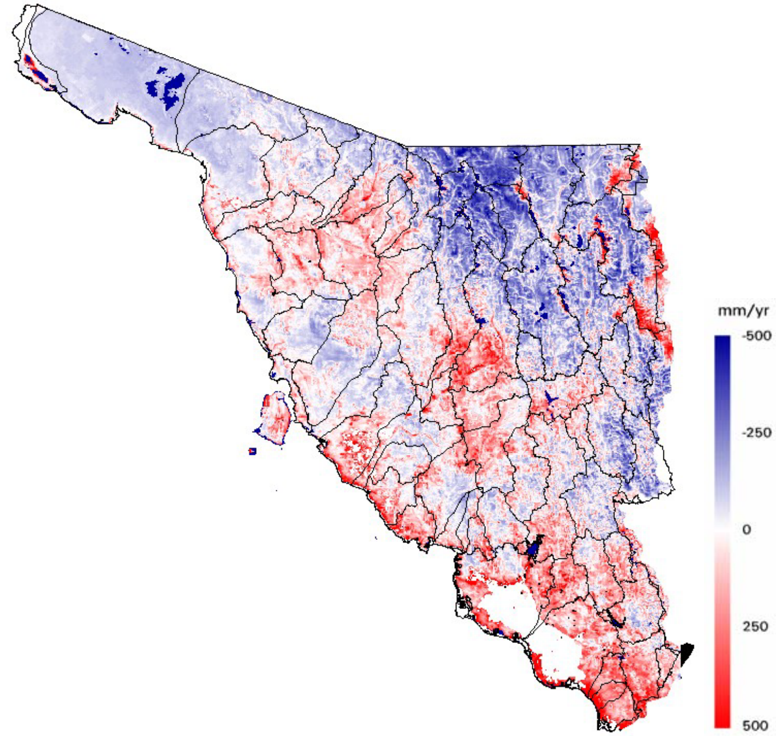


Fig. 4. Net groundwater use of natural vegetation for all administrative boundaries in Sonora State. Irrigated areas and built-up areas are left blanc. Red (positive) is extraction and blue (negative) is recharge

Methodology

WaterWatch has used the SEBAL technology to map the month-to-month variation of ET fluxes for 2 years with different rainfall. Actual evapotranspiration (ET_{act}) consumes water that originates from different sources:

- Intercepted precipitation (E_i)
- Infiltrated precipitation (E_p)
- Groundwater extraction through natural vegetation (E_{ng})
- Groundwater extraction through artificial pumping (E_{ag})
- Surface water resources diverted from rivers (E_s)

The actual evaporation (ET_{act}) that is derived from SEBAL is thus composed off:

$ET_{act} = E_i + E_p + E_{ng} + E_{ag} + E_s$

The approach taken in this study, is to derive ETact from SEBAL in an independent manner and then afterwards expose it to an ET source analysis to determine which part of ET_{act} is contributed by groundwater resources (E_{ng} & E_{ag}). This concept was applied to every 100 ha area in the vast Sonora State.

Results

The average Net Groundwater Use (NGU) of natural vegetation Eng of all negative (net recharge) and positive (net depletion) is 8 mm/yr only, which reveals that the volumetric sink is 1309 Mm^3/yr. The distribution of NGU across entire Sonora State is demonstrated in Fig. 4.

The following computational loop is strictly followed:

1. Actual evapotranspiration (ET_{act}) from SEBAL
2. Gross precipitation (P_{gross}) from rain gauges
3. Interception (E_i) from P_{gross}, LAI and vegetation cover
4. Surface runoff (R) from P_{gross}, E_i, soil moisture and terrain slope
5. Infiltrated precipitation from P_{gross}, E_i and R
6. Net Groundwater Use (NGU) natural vegetation (E_{ng}) from ET_{act}, P_{gross}, E_i, R
7. Infiltrated surface water irrigation from canal discharges and field losses, E_s
8. Net Groundwater Use (NGU) irrigated crops (E_{ag}) from ET_{act}, P_{gross}, E_i, R and E_s

Net Groundwater Use can be further partitioned into the different natural ecosystems. Each ecosystem has its own hydrological environment and taps groundwater to remain vivid (see Table 2). Within a single ecosystems, one can find both recharge and extractions happening simultaneously. Another issue that make these processes difficult to quantify is the month-to-month variation of recharge and extraction due to rainfall and storage change mechanisms. Mixed forests (59 mm) and deciduous broad leaf forests (63 mm) consume layer wise the highest groundwater amount. From a volumetric point of groundwater consumption, open shrubland (NGU=1.02 km^3/yr) ranks second after the deciduous broad leaf forests (2.88 km^3/yr). The largest net recharge

Table 2. Net Groundwater Use (NGU) in natural ecosystems averaged for 2000 and 2003. The standard deviation is provided between brackets (positive is net extraction, negative is net recharge)

	Area km^2	NGU mm	NGU Mm^3
Grasslands	15,930	-86 (156)	-1,369
Barren or Sparsely Vegetated	5,630	-72 (64)	-405
Evergreen Needle leaf Forest	7,190	-65 (181)	-467
Woody Savannas	32,840	-28(178)	-920
Open Shrublands	56,840	18 (149)	1,023
Mixed Forest	9,050	59 (188)	533
Deciduous Broad leaf Forest	45,820	63(166)	2,887
Permanent Wetlands	50	537 (313)	27
BALANCE	17,335		1,309

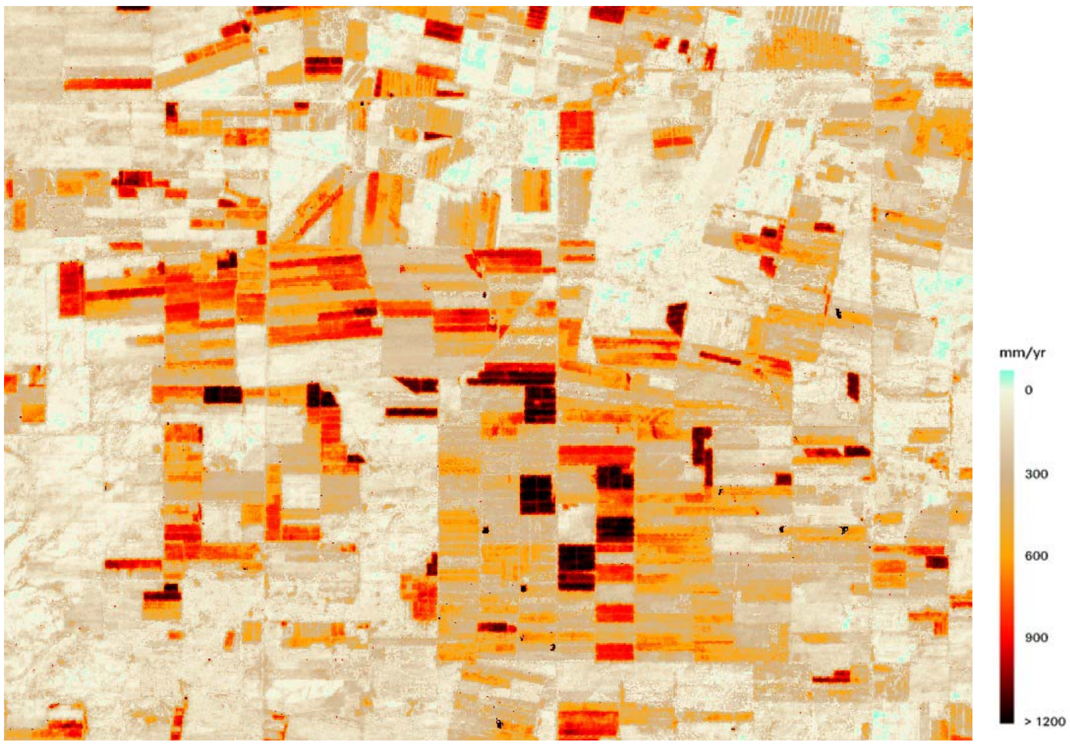


Fig. 5. Net Groundwater Use of irrigated crops in Costa de Hermosillo from October 1999 to September 2000.

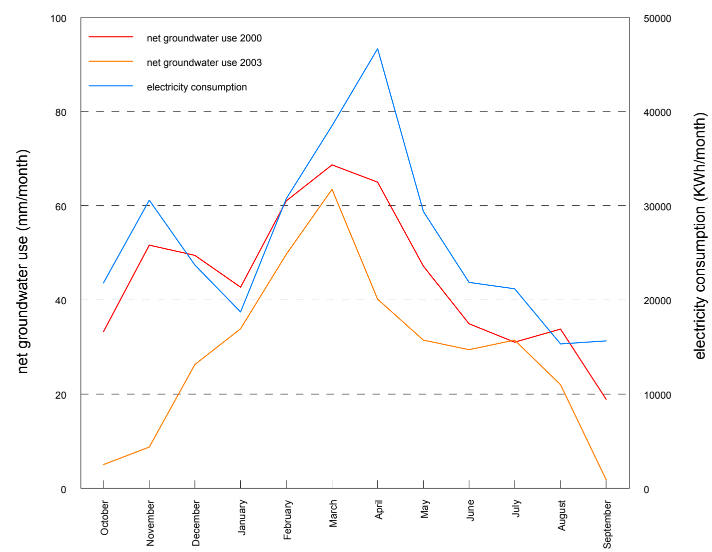


Figure 6. Net groundwater use in 2000 and 2003 versus the electricity consumption for Costa de Hermosillo

occurs in the IGBP class of grasslands (NGU=-1.36 km^3/yr), followed by woody savannas (NGU=-0.91 km^3/yr).

Fig. 5 shows the results within a given irrigation scheme. Certain farm plots are visible that pump significantly more groundwater (>1000 mm/yr) than other farmers (±500 mm/yr on average). This is related to the type and the duration of the crops. Orchards with perennial fruit trees need much more water than for instance chickpeas. This are well irrigated and precisely managed high value crops with pressured drip and micro-sprinkler systems.

Remotely sensed NGU values of Costa de Hermosillo were compared against the registered power consumption. A statistical relationship on the basis of monthly time steps could be found (r^2=0.81), despite the period was only partially overlapping. This reveals that the temporal trend in NGU – and thus of groundwater extraction for irrigated crops – was fairly good.

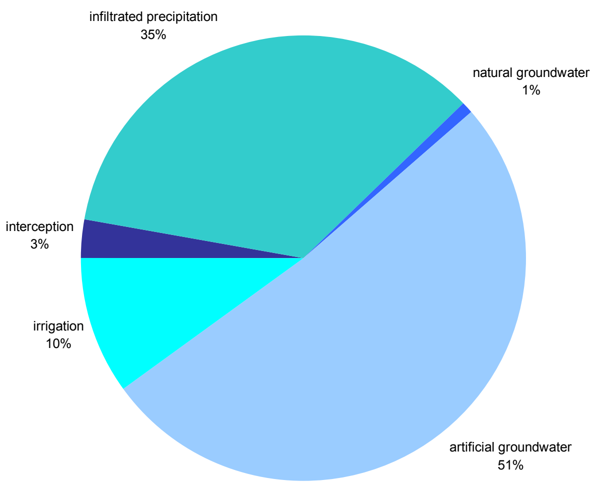
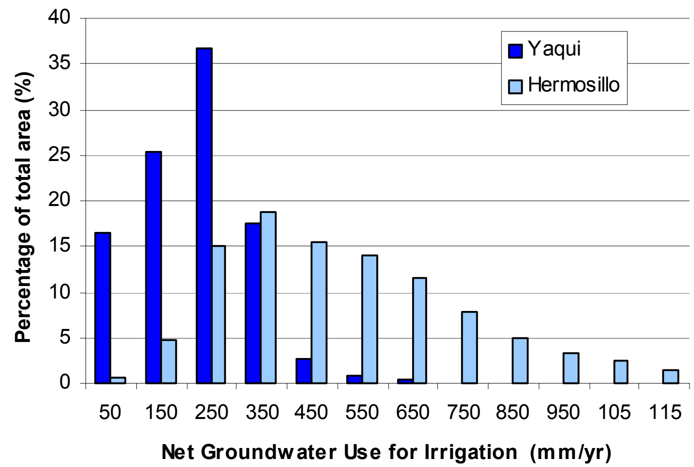


Table 3. Summary table net groundwater use

Area	Water use type	Acreage ha	NGU mm/yr	NGU Mm^3/yr	Recharge Mm^3/yr	Extraction Mm^3/yr
Valle del Yaqui	Irrigation	225,000	176	396 (20 %)	170	566
Costa de Hermosillo	Irrigation	44,681	507	226 (12 %)	88	314
Sonora State	Natural vegetation	17,335,000	7.5	1,309 (68 %)	3,161	4,470
TOTAL		17,604,681		1,932 (100 %)		

The population of NGU values in Costa de Hermosillo and Valle del Yaqui are both log-normally distributed. The standard deviation in Hermosillo of the spatially distributed NGU values is with 234 mm more than the 122 mm deviation in Yaqui. The lower spatial spread in Yaqui can be ascribed to the dominancy of wheat-maize rotations. The extractions in Costa de Hermosillo were 507 mm on average, which for an area of 44,681 ha results in a sink of 226 Mm^3/yr. The extractions in Valle del Yaqui were per unit land 176 mm only, but due to a larger area of 225,000 ha, yields into a larger total extracted volume of 396 Mm^3/yr.



Conclusions

This case study with detailed maps of Costa de Hermosillo (30 m) and more regional maps for the entire state of Sonora (1000 m) demonstrates the power of remote sensing to assess spatially distributed groundwater extractions without the need to meter individual wells and interviewing farmers on their pumping hours (with a biased reply as a possibility). The NGU validation could be obtained for the 'bulk extraction' of Costa de Hermosillo. A good relationship was established between electricity consumption and NGU (r^2= 0.81). The extraction in Valle del Yaqui of 566 Mm^3/yr during the very dry 2003 is more than the long term value of Red Mayor and Red Minor (228 Mm^3/yr), which is believed to be reasonable because of drought. The ET computations for Yaqui were only a few percent different with the eddy covariance-based field ET measurements.

Overall, NGU in Sonora State from natural vegetation is higher (68%) than for irrigated crops (32%). A total NGU of 1,932 Mm3 is equivalent to 10.9 mm/yr. At a specific yield of 0.15, this implies that the average groundwater table depth in Sonora declines with a rate of 7.3 cm/yr. This method will now be further extended to other aquifers in Northern Mexico. Because there is a global need for any aquifer extraction information, this method is also valuable for evaluation groundwater-based irrigation activities in India, China, Iran and Pakistan.

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