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contents continue on back cover

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contents continued from front cover

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Groundwater Banking in the Rio Grande Basin

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Abstract: The water planning and management policies of the Rio Grande basin no longer respond to the sustainable needs of water users, environment, and international commitments of this transboundary basin between Mexico and the United States. This paper describes how groundwater banking through an *in lieu* method is one approach leading to better water management in this basin. In lieu groundwater banking is a conjunctive water allocation policy applicable to water users supplied from surface water and groundwater sources. A basin simulation model of the Rio Grande basin, built in the water evaluation and planning system (WEAP) software, was used to evaluate the groundwater banking policy. Two scenarios are discussed: a baseline scenario without new water allocation policies implemented and a groundwater banking scenario considering the in lieu groundwater banking method implemented in the Meoqui aquifer. Results show that groundwater banking can significantly improve water management in the basin, increasing system storage, improving water supply for users in the basin, and enhancing compliance with the treaty obligations.

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Introduction

Background

The Rio Grande basin is a transboundary basin between the United States and Mexico [Fig. 1(a)]. It is a fundamental resource for the economy, environment, health, and quality of life for the people in both countries and along the border. Cities, such as Albuquerque, Las Cruces, El Paso, Brownsville, and McAllen in the United States and Monterrey, Ciudad Juarez, Matamoros, and Reynosa in Mexico, depend on the water resources of this basin. The important agriculture economies of the El Paso/Juarez Valley, the lower Rio Grande Valley, and the Rio Conchos irrigation districts also depend on the waters of this basin. The environmental health of the Big Bend National Park is affected by the quantity, quality, and timing of the Rio Grande streamflows. In addition, international obligations under the U.S.-Mexico Convention of 1906 and the Treaty of 1944 apply for both countries [International Boundary and Water Commission (IBWC) 1906, 1944; Oregon State University (OSU) 2005].

Due to its geographical position, the Rio Grande basin (known as the Rio Bravo basin in Mexico) is one of the most stressed basins in the world [World Wildlife Fund (WWF) 2007] not only due to the increase of population and industry but because of the natural water scarcity in the region [Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT) 2004]. Historically, cyclic periods of drought and wet conditions have occurred in the basin, for instance, dry conditions from the late 1940s to the mid-1960s, wet conditions from the mid-1960s to the early 1990s, and dry conditions again from the mid-1990s to the mid-2000s (Tae-Wong et al. 2002; Vigerstol 2002). The latest drought (1994–2003) put water administrators, stakeholders, and decision makers in an extremely problematic situation because of its severity and length. In the 5-year cycle from 1992 to 1997, Mexico was not able to deliver to the United States the amount of water as mandated by the 1944 Treaty (SEMARNAT 2004). Furthermore, in the following treaty cycle, the water debt of Mexico increased, and the situation at that point was very tense between both countries. Meetings between the presidents of both countries took place in order to discuss possible solutions, and drastic measures were taken by the Mexican government to reduce the water debt. In 2002, such measures included stopping the supply for Mexican irrigation districts 025 Bajo Rio Bravo and 004 Don Martin and transferring Mexican storage to the United States in the international Amistad and Falcon reservoirs (IBWC 2002). During 2005, the water debt of Mexico was paid, but it was evident that water planning and management of the Rio Grande basin no longer meets the complex and challenging situation in the basin.

In 2002, a consortium of eight institutions from both the United States and Mexico (universities, nongovernmental organizations, and governmental research agencies) was formed to assess opportunities to improve water management in the Rio

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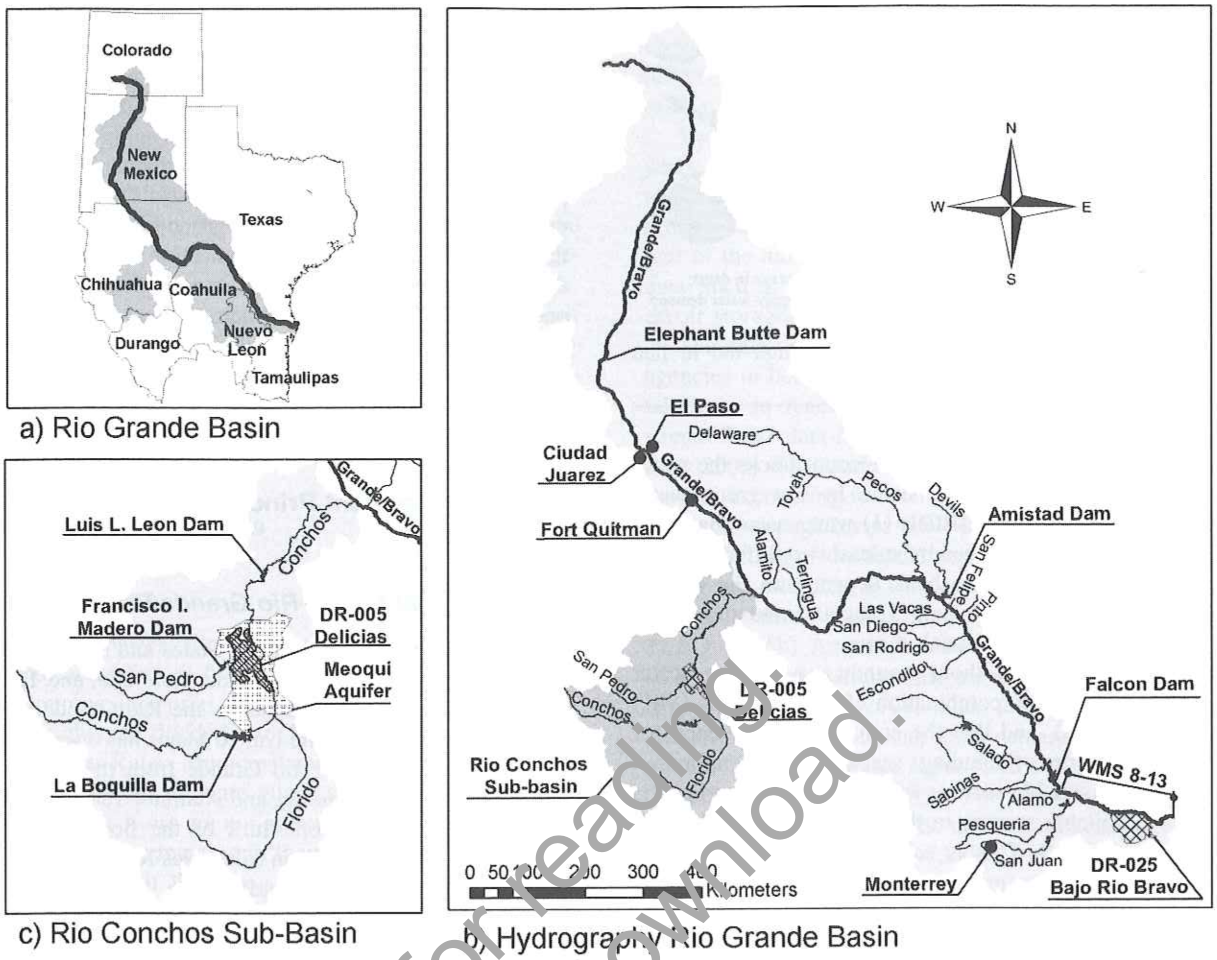


a) Rio Grande Basin

c) Rio Conchos Sub-Basin

b) Hydrography Rio Grande Basin

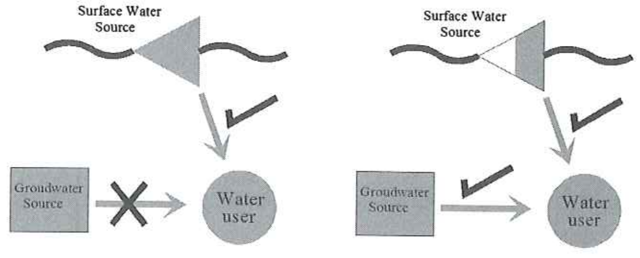
Fig. 1. Rio Grande basin

Grande basin. An important tool for this assessment is a basin-wide model to simulate water allocation in the basin and evaluate the effects of alternative management policies (Danner et al. 2006). Extensive basin stakeholder interviews with water users, planning agencies, research institutes, nongovernmental organizations, and local, state, and national government institutions were used to define a broad suite of scenarios with some possibility of improving water management in the basin [Thomas and McKinney 2006]. This paper presents the results of assessing one of these proposed scenarios, *in lieu* groundwater banking.

In Lieu Groundwater Banking

In many regions, it has been recognized that due to their hydraulic and operational interdependence, conjunctively managing surface and groundwater can lead to increased benefits (Wagner and Vaquero 2002; Pulido-Velázquez et al. 2006). Conjunctive management of ground and surface water has been studied for some time (Buras 1963); mostly, as optimization models for small- (Pulido-Velázquez et al. 2006), medium- (Reining et al. 1999), and large-scale areas (McPhee and Yeh 2004). Since the 1970s, groundwater banking studies have considered the economic and hydraulic feasibility of storing water in aquifers in wet periods and recovering it later in dry periods (Thomas et al. 2001). Since then, groundwater banking projects have been implemented in water stressed areas such as the Semitropic Groundwater Bank [Semitropic Water Storage District (SWSD) 2004], Kern Water Bank [(KWB) 2008], and Arvin-Edison Water Storage District (Thomas et al. 2001) in California. In these cases, the groundwater bankers are irrigation districts with groundwater rights, the programs are supported by external clients, such as the Metropolitan Water District of Southern California, and they involve the storage of a client's surplus of water in wet years in local aquifers and recovery in dry years. The development of groundwater banks requires the assessment of hydrogeology and water quality, legal and financial issues, as well as proper water planning and management.

The in lieu groundwater banking method stores natural recharge in aquifers. Consider a water user that has a right to two different water sources: surface water from a reservoir and groundwater from an aquifer [see Fig. 2(a)]. Recharge to a groundwater bank in the aquifer may take place in wet years when there is sufficient surface water to supply the water demand. In this case, aquifer pumping is stopped and natural recharge accumulates in the bank. The maximum water credited to the bank will be equal to the user's groundwater right. Withdrawal from the bank takes place in dry years when there is insufficient surface water to supply the demand [see Fig. 2(b)]. In this case, water from the reservoir is used to supply as much water as possible, and withdrawals from the bank are used to cover any deficit. To model this situation, aquifer storage is divided into two accounts: an aquifer account and a groundwater bank account. The aquifer account tracks water in the aquifer as if the banking



a) Normal or high available storage in dams; dams supply all water demand

b) Low available storage in dams; aquifer and dams supply water demand

Fig. 2. Scheme of the groundwater banking through the in lieu method

did not take place. In contrast, the bank account tracks the water deposits and withdrawals from the bank. In lieu groundwater banking has three main characteristics: (1) water users that want to use this method must be supplied by at least two different water sources; (2) the operation of the bank depends on the surface water available to the water user; and (3) the accumulation in the bank by natural, rather than artificial, means.

Assume that in period t, without groundwater banking, water demand is to be met from a combination of surface water (SW_t) and groundwater (GW_t), and that the conveyance efficiency for surface water deliveries (including seepage and evaporation losses) is CE. The available surface water (Av_S_t) in period t is the sum of the available storage in the reservoirs supplying the user ($Av\_S_t^i$, $i=1,\ldots,I$). This is equal to the reservoir initial storage (S_{t-1}^i, $i=1,\ldots,I$) minus any required minimum storage ($S_{\min}^i$, $i=1,\ldots,I$)

$$Av\_S_t = \sum_{i=1}^{I} Av\_S_t^i = \sum_{i=1}^{I} (S_{t-1}^i - S_{\min}^i) \qquad (1)$$

To track the water deposited in and withdrawn from the groundwater bank, the following three cases are considered:

1. *Available surface water exceeds requirement*

$$Av\_S_t \geq (SW_t + GW_t)/CE \qquad (2)$$

In this case, in lieu groundwater banking is invoked, curtailing groundwater pumping and providing all water from surface water sources. A deposit of GW_t is credited in the bank

$$\text{Bank}_t = \text{Bank}_{t-1} + GW_t \qquad (3)$$

2. *Available surface water is more than the surface water demand (plus losses), but less than total demand*

$$SW_t/CE \leq Av\_S_t < (SW_t + GW_t)/CE \qquad (4)$$

In this case, water is supplied from both surface and groundwater and the bank is unaffected. For simplicity in the groundwater bank operation, we consider that either the complete amount of GW_t is deposited in the bank or none.

3. *Available surface water is less than surface water right (plus losses)*

$$Av\_S_t < SW_t/CE \qquad (5)$$

In this case, water is supplied from surface water to the extent possible, but there will be a surface water deficit, $Av\_S_t - SW_t < 0$, that must be covered from a combination of groundwater and withdrawals from the bank

$$\text{Bank}_t = \text{Bank}_{t-1} - (SW_t - Av\_S_t) \qquad (6)$$

In order for a groundwater bank to be created, a number of incentives (legal, institutional, and economic) may be necessary. In particular, the bank's depositors must have assurance that water deposited in the bank will be available to them for withdrawal at a later time. On the other hand, the managing authority may simply buy the rights and deposit them in the bank for later sale. The possibility of withdrawing extra water from the bank during drought periods may encourage groundwater users to switch to this method. The costs of implementing a groundwater bank or the details of the aquifer hydraulic conditions as a result of bank operations are not considered here; rather, we are seeking to assess the feasibility of the overall management policy. If it appears feasible, then these and other issues (legal, institutional, and political) will be investigated.

Water Management Principles of the Rio Grande Basin

Treaty of 1944 for the Rio Grande/Bravo

The 1944 Treaty between United States and Mexico specifies the water allocation for the Rio Grande, Colorado, and Tijuana rivers (IBWC 1944). Articles 4–9 define the Rio Grande water allocation for both countries. The United States has ownership of (1) all the waters reaching the Rio Grande from the Pecos and Devil Rivers, Goodenough Spring, and Alamito, Terlingua, San Felipe, and Pinto Creeks; (2) one-third of the flow reaching the Rio Grande from the six Mexican tributaries Rio Conchos, San Diego, San Rodrigo, Escondido, and Salado Rivers and Arroyo Las Vacas Creek provided that this third shall not be less than 431.721 million m^3/year as an average over cycles of 5 consecutive years; and (3) one-half of all other flows not otherwise allotted along the Rio Grande. Mexico has ownership of (1) all the waters reaching the Rio Grande from the San Juan and Alamo Rivers including the return flows from lands irrigated from these rivers; (2) two-thirds of the flow reaching the Rio Grande from the six tributaries named above; and (3) one-half of all other flows not otherwise allotted occurring along the Rio Grande.

Amistad and Falcon international dams, authorized as joint projects in the 1944 Treaty, are used to store and manage the water for both countries and each country has its own storage account in each reservoir. Amistad dam has a conservation capacity of 3,887 million m^3, of which 56.2% belongs to the United States and 43.8% belongs to Mexico. Falcon dam has a conservation capacity of 4,889 million m^3, of which 58.6% belongs to the United States and 41.1% belongs to Mexico. The treaty cycles mentioned above can expire in less than 5 years if the U.S. storage in both dams is filled with water belonging to the United States.

The Mexican water deliveries specified in the treaty must be fulfilled from the one-third outflow of the six Mexican tributaries listed above. At the end of a 5-year cycle, the delivery from these tributaries is evaluated to determine compliance with the treaty obligations. If there is a deficit in the treaty delivery, it must be paid in the following cycle using the one-third outflow of water coming from the six tributaries.

Water Authorities

The International Boundary and Water Commission is the international organization in charge of the 1944 Treaty execution, which includes water and storage accounting for each countries, treaty accounting, and maintenance and operation of the hydraulic infrastructure along the border, among other activities. In Mexico, the National Water Commission "*Comision Nacional del Agua*" (CONAGUA) is the federal authority responsible for water management on the Mexican side of the Rio Grande. CONAGUA carries out water planning and management along the border according to the accounting of water provided by the IBWC.

In the United States, the Texas Commission on Environmental Quality (TCEQ) is the state agency in charge of water management in Texas. The Texas Rio Grande Watermaster Program regulates the U.S. water diversion from Amistad reservoir to the Gulf of Mexico (TCEQ 2005a). Similar to CONAGUA, TCEQ performs water planning and management along the Rio Grande portion of the border according to the accounting of water provided by the IBWC.

Rio Grande Water Demands

U.S. Demands

The Texas Watermaster allocates water on an account basis (TCEQ 2006) according to five water use types: irrigation, municipalities, mining, industrial, and other. Also, below Falcon Reservoir water rights are divided into Types A and B based on the Texas Watermaster Rules. Municipal and industrial accounts have the highest priority and they are guaranteed an amount for each year. The rest of the users are not guaranteed and their allocation depends on the water remaining in their accounts from the previous year. Every month the Texas Watermaster determines the amount of unallocated water in the U.S. account of the international reservoirs after the municipal and industrial allocation has been subtracted. If there is surplus water remaining, it is allocated to agricultural users of Type A, then Type B, then mining, and finally other uses.

Mexican Demands

Mexican water demands are characterized by use. In this research, only agricultural and municipal water users are considered since these are the dominant uses in the basin. The National Water Regulation of Mexico "*Ley de Aguas Nacionales*" establishes the priority for all water uses (LAN 2004). Municipal and domestic users have the highest priority and they are guaranteed an amount for each year. Agricultural users are not guaranteed and their allocation depends on the available storage in the respective dam that supplies them.

At the beginning of each October, CONAGUA determines the available reservoir storage after deducting municipal allocations, evaporation, and operation losses (Collado 2002). Then, a negotiation between CONAGUA and the irrigation districts sets the agricultural water allocation for the coming water year. In 2002, CONAGUA conducted a water use survey and defined annual water concessions (legal definition of water rights in Mexico) for each agricultural water user (SEMARNAT 2002). CONAGUA tries to deliver this volume of water if there is enough water in the available storage in the respective reservoirs.

Simulation Model of the Rio Grande Basin

In order to evaluate the water management of the basin, a hydrologic planning model has been built for the Rio Grande basin. The water evaluation and planning system (WEAP) (Seiber 2006) is used to model water management in the Rio Grande basin. Details of WEAP and its application to other basins can be found in Yates et al. (2005) and Purkey et al. (2006), respectively.

The period of analysis for the scenario considered here is 60 years from October 1940 to September 2000. This period of analysis contains drought of record (1948–1957), a smaller drought in the 1960s (1961–1965), a wet period (1966–1991), and part of the most recent drought (1994–2007). Hydrological input data, such as naturalized flow, evaporation, streamflow data, reservoir storages, etc., were available for this period.

The data used in the Rio Grande model come from different agencies in both countries. Main tributary inflows and incremental flows in reaches were taken from the TCEQ "naturalized stream flow" data for the Rio Grande basin (R. J. Brandes Company 2003). The model contains channel loss factors for the river reaches accounting for conveyance, evaporation, evapotranspiration, and seepage losses (IBWC 2005; CONAGUA 2007; TCEQ 2003). Details of the model components, coefficients, and performance are available in Danner et al. (2006).

U.S. water demands in the model were derived from the TCEQ (2005b). Annual demands used in the model correspond to 60% of the maximum annual use in the period 1990–2000 (R. J. Brandes Company 2003) and these are disaggregated into monthly demands. Mexican water demands were derived from the public database of water rights (REPDA 2004), which is the official database of CONAGUA. For Mexico, annual water uses for 2004 were disaggregated into monthly values. Return flow factors were derived from TCEQ (2005b), Instituto Mexicano de Tecnologia del Agua (IMTA) (Collado 2002), CONAGUA (REPDA 2004), and water users (CONAGUA 2005; L. R. Caballero, personal communication, May 2005).

The Rio Grande model includes 197 water demands. Due to the large number of individual water users along the river in both countries, many of the water demands were aggregated in the model. U.S. demands were aggregated based on use type, i.e., municipal, irrigation, etc., type of water right (A or B), and location in the basin relative to the river reaches defined by the TCEQ Rio Grande Watermaster. The Watermaster Rules define 13 river reaches, referred to as Watermaster Sections (R. J. Brandes Company 2003). Similarly, Mexican demands were aggregated by type of use and location in the basin relative to the river reaches. Since the priority system for both countries is based on the type of use, there is no bias in the aggregation of water demands. Surface water and groundwater use in both countries is considered in the model. Most of the semiformal irrigation districts in Mexico (called Uderales) and many of the individual water users in the United States use groundwater as their main source of water supply. Groundwater is represented in the model as simple "tanks" for each regional aquifer in the basin.

There are 24 reservoirs in the model with a total storage capacity of approximately 26.3 billion m^3. Sixteen of the reservoirs are located in Mexico (11.4 billion m^3, total storage capacity), six are in the U.S. (3.4-billion m^3 capacity), and two of them are binational, Amistad and Falcon (11.6-billion m^3 total capacity).

The model contains rules to replicate the accounting and allocation logic of the 1944 U.S.-Mexico Treaty. This logic includes tracking inflows from the treaty tributaries, allocating those flows to the respective countries, accounting for storage for each country in the international reservoirs, calculating evaporation losses for each country, accounting of the Mexican treaty deliveries per year and cycle, and resetting treaty cycles when the international reservoirs are filled.

Although the model contains inflow data for 60 years, model calibration was done for 15 years from October 1978 to September 1993 (Danner et al. 2006). During this period construction of most of the basin infrastructure had been completed including both international dams. Although there was no specific water allocation policy in Mexico during this period, the records of historic diversions exist for almost all of the water users. For Mexico, historical diversions were provided by CONAGUA (2008) and for the United States these data were derived from the IBWC withdrawal records available online (IBWC 2008). In general, two important sets of parameters were calibrated in the model: the conveyance losses along the streams and the rules governing the release of water from the conservation pools of the Mexican and international dams. This section briefly describes the testing process for the Rio Grande model. A complete description of this process is presented in Danner et al. (2006).

To test the model, historic water demands for this period were loaded into the model, and model results were compared to historical values for reservoir storage and gauged streamflow. Danner et al. (2006) presented the comparison of the historic and the model values for 12 reservoir storages and 8 streamflow gauges. During the calibration and validation process, the storage in the international reservoirs Amistad and Falcon was used as indicators to evaluate the performance of the model because (1) they store the water for each country according to the Treaty of 1944 and (2) both reservoirs are influenced by the water management in the entire basin. Thus, if there is a problem in the modeling of certain region or with the water allocation for each country, the storage in the international reservoirs shows it immediately.

Two coefficients are to evaluate the goodness of fit for the model validation (Legates and McCabe 1999): the coefficient of efficiency (Nash and Sutcliffe 1970) and the coefficient of agreement (Willmott et al. 1985). These coefficients compare the observed against the predicted values from the model. The coefficient of efficiency ranges from minus infinity to 1, with higher values indicating better agreement. The index of agreement varies from 0 to 1 with higher values indicating a better agreement between the model and the observations (Legates and McCabe 1999). The coefficients of efficiency and agreement for Mexico's storage in the international reservoirs are 0.825 and 0.953, and for the United States are 0.805 and 0.945, respectively. These values indicate that the model is representing adequately the water resources system. Considering that during this period most of the dams had no defined operating policy, the reservoir storage results are satisfactory for the purpose here. Model and historical streamflow were compared at four stations along the Rio Grande stream and six in the main tributaries. For the four control points at the Rio Grande stream (Johnson Ranch, Foster Ranch, Laredo, and Below Falcon), the coefficients of efficiency and agreement are bigger than 0.297 and 0.741, respectively. For the six main tributaries (Arroyo Las Vacas, San Diego, San Rodrigo, Escondido, and Salado), the coefficients of efficiency and agreement are bigger than 0.536 and 0.883, respectively. Differences between the simulated and historical values are bigger in drought periods than in wet periods. Results from the testing suggest that in the overall, the model is representing properly the water allocation of the Rio Grande basin. This result is important considering the lack of defined operating policies for many of the dams in the basin.

In Lieu Groundwater Banking in the Rio Conchos Basin

As mentioned earlier, a suite of scenarios was developed by a binational consortium of researchers for the possible improvement of water management in the Rio Grande basin. The model discussed in the previous section has been used to evaluate some of these scenarios. The results of assessing one of them—in lieu groundwater banking—are discussed in this section. The assessment is an incremental comparison of a baseline scenario, where current practices of water allocation are implemented, and the groundwater banking scenario, where in lieu groundwater banking in the Rio Conchos basin is implemented.

Mexican irrigation district 005 Delicias (DR-005) is located in the Rio Conchos basin, a subbasin in the middle part of the Rio Grande basin [see Fig. 1(c)]. DR-005 has a combined surface and groundwater concession of 1.13 billion m^3 and it is supplied by two sources, 189 million m^3/year from groundwater out of the Meoqui aquifer and 941 million m^3/year from surface water via the La Boquilla and Francisco I. Madero reservoirs (744 and 197 million m^3/year, respectively). The conveyance efficiency of delivering surface water is estimated to be 80% (Collado 2002); no conveyance loss is assumed for delivering groundwater. Thus, the threshold of available storage that controls deposits to the groundwater bank is $(SW_t+GW_t)/CE=1.409$ billion m^3 and the threshold to control withdrawals from the bank is $SW_t/CE=1.173$ billion m^3. For DR-005, the available surface water in the system is the sum of the available storage in F. I. Madero and La Boquilla reservoirs. The minimum operating storages for La Boquilla and F. I. Madero reservoirs are 165 and 8.5 million m^3, respectively.

In the case of the Rio Conchos basin, an agreement between CONAGUA and DR-005 Delicias could be undertaken to implement the groundwater bank. DR-005 water users would seek permission from CONAGUA to temporarily interrupt groundwater deliveries and, in exchange, use surface water, while CONAGUA must ensure the return of the groundwater to the users in case of drought. According to Mexican water law, water in the bank would belong to CONAGUA (LAN 2004).

Results

The results of applying the in lieu groundwater banking method in the Rio Conchos basin are presented in this section. The advantages and disadvantages are estimated for water users in both nations and for the treaty obligations. First, the effects on system storage are discussed. This is followed by a description of several performance criteria (reliability, resilience, and vulnerability) and a sustainability index.

System Storage

The system storage considered here is the sum of the storage in the Mexican dams: La Boquilla, F. I. Madero, Luis L. Leon, the international dams: Amistad and Falcon dams, and the storage in the Meoqui aquifer. These dams are selected because they have significant storage capacity and they are affected by water management policies in the Rio Grande basin. In addition, the Meoqui aquifer is included since it is used for the groundwater bank. Considering the system storage under the baseline scenario to be 100%, the groundwater banking policy is measured relative to that (see Table 1). Groundwater banking leads to a 19% increase

Table 1. System Storage under the Baseline and Groundwater Banking (GW Bank) Scenarios

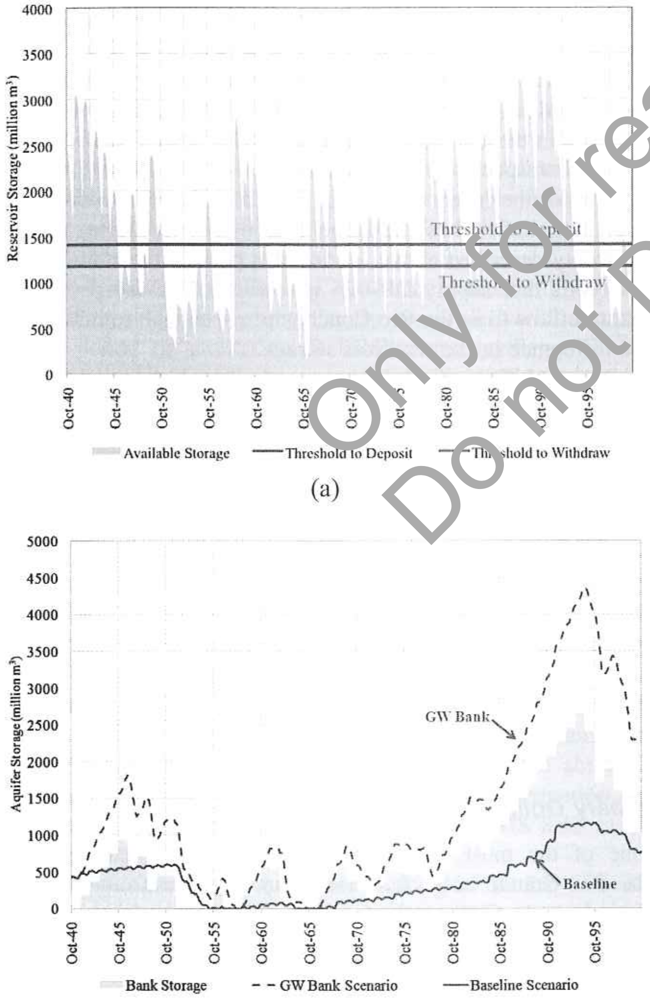
	Storage (%)				Evaporation (%)	Spills (%)
	Dam	Aquifer	GW bank	Total		
Baseline	96	4	0	100	100	100
GW bank	93	13	12	119	92	71

Table 2. Groundwater Bank Balance for the Groundwater Banking Scenario

Groundwater bank	Volume (million m^3)	Period (year)
Deposits	5,857.7	31
Withdrawals	4,646.5	18
No activity	—	11
Balance	1,211.3	60

in system storage over a 60-year period. Even though the groundwater bank scenario has lower reservoir storage than the baseline scenario, it has larger system storage because of the groundwater bank. Considering the total volume of evaporation and spill under the baseline scenario to be 100%, the groundwater banking policy reduces these values to 92 and 71%, respectively.

Fig. 3 shows the reservoir, aquifer, and groundwater bank storage for the two scenarios. During wet periods, when the available storage is larger than the threshold to deposit water in the bank [Fig. 3(a)], surface water is used, allowing deposits to the bank [Fig. 3(b)]; surface water storage is lower than in the baseline scenario, decreasing the probability of spills and reducing evaporation losses. In dry periods, when the available storage is smaller than the threshold to withdraw water from the bank, a combination of surface water, groundwater, and bank water is used to meet demand. Pulido-Velázquez et al. (2006) noticed a similar behavior in a conjunctive surface-groundwater model when the water allocation policy was set to minimize groundwater use; they also found the policy to be economically optimal. In the Rio Conchos, there is an intensive use of groundwater during drought periods (1947–1958, 1961–1965, and 1994–2000). From 1978 to 1994 (16 years), there were no bank withdrawals and all banked water was saved for future use, e.g., in the drought of the 1990s.



(a)

(b)

Fig. 3. (a) Available storage in dams; (b) aquifer storage including groundwater bank under the baseline scenario and groundwater banking scenario (GW bank)

Table 2 shows the deposits, withdrawals, and balance of the groundwater bank over the 60-year simulation period. During 31 years, 5.8 billion m^3 of water were deposited in the bank (an average of 189 million m^3/year). On the contrary, during 18 years, 4.6 billion m^3 of water were withdrawn from the bank to cover the surface water deficits (an average of 258 million m^3/year). At the end of the simulation period, there is a positive balance in the bank of 1.2 billion m^3 of water.

The actual capacity of the pumping facilities in the Meoqui aquifer is 130 million m^3/year (Caballero 2005), less than the groundwater concession value (189 million m^3/year) used to estimate deposits to the bank. We consider the groundwater concession amount here in order to evaluate the groundwater banking policy and its possible negative effects on water users downstream. In fact, if the groundwater bank turns out to be feasible and efficient, then we can expect increased pumping capacity to be installed in the aquifer, so this higher limit on deposits is a reasonable assumption.

Extractions from the groundwater bank vary from 17.5 to 694.2 million m^3/year. From a duration curve of bank withdrawals, the 25th, 50th, 75th, and 95th percentiles correspond to withdrawals of 117, 223, 450, and 694 million m^3/year, respectively. So, if the pumping capacity increases by 223 million m^3/year (to 353 million m^3/year considering the actual pumping capacity of 130 million m^3/year), there is 50% probability that any deficit to DR-005 will be covered. Other groundwater banks, such as the Semitropic Groundwater Bank or the Kern Water Bank, have recovery capacities of 247 (SWSD 2004) and 296 million m^3/year (KWB 2008), respectively. For recovery, the major issue is related to avoiding injury to other groundwater users, clear rules and limits on the recovering of water must be defined, and water tables would not be allowed to fall below the levels that would occur in the absence of a conjunctive use program. The recharge and recovery operations would be controlled by the local groundwater management authority. In addition, it is necessary to avoid potential environmental impacts with moving water into and out of groundwater banks. The recovery capacity depends on several factors such as geohydrology, aquifer capacity, water demand, and investment, among others. We suggest, as a first approach, a recovery capacity of 223 million m^3/year over the concession amount for the Meoqui aquifer because this capacity covers the

Table 3. Reliability, Resilience, Vulnerability, Maximum Deficit, and Sustainability for the Various Stakeholders in the Rio Grande Basin under the Baseline and Groundwater Banking (GW Bank) Scenarios

Stakeholder	Scenario	Reliability (%)	Resilience (%)	Vulnerability (%)	Maximum deficit (million m^3)	Sustainability (%)
DR-005	Baseline	72	29	36	89	51.4
	GW bank	87	38	38	59	58.6
DR-025	Baseline	93	25	25	34	55.9
	GW bank	90	50	19	36	71.3
WMS 8–13	Baseline	85	22	15	37	54.3
	GW bank	85	23	13	35	55.3
Treaty	Baseline	83	50	38	41	63.6
	GW bank	83	50	36	41	64.3

50% of the surface water deficits and it has been installed in other groundwater banks, which is physically and technically feasible. Additional technical, geohydrologic, and economic studies must be done to determine the best recovery capacity.

Performance Measures

Results from the groundwater banking scenario for irrigation districts 005 Delicias (DR-005) and 025 Bajo Rio Bravo (DR-025) in Mexico and Texas Watermaster sections 8-13 (WMS 8-13) in the United States [see Fig. 1(b)] are discussed in this section. These are the largest and economically most important water users in the basin. Three performance criteria are used to characterize this scenario: reliability, vulnerability, and resilience (Loucks and van Beek 2005).

Reliability is the frequency with which a water demand is satisfied over the simulation period (Hashimoto et al. 1982). Table 3 shows the reliability for the selected irrigation districts under the groundwater banking scenario. Under this scenario, reliabilities for most of the stakeholders increase or are unchanged (DR-005 increased by 15%, WMS 8-13, and deliveries to the treaty obligations did not change). The slight decrease in the reliability of DR-025 (3%) is due to the following. In wet periods there is a lower storage in Amistad and Falcon reservoirs, the source of water for DR-025, because of the intensive use of surface water in the Rio Conchos due to operation of the groundwater bank. In dry periods, even though the outflow from the Rio Conchos is larger under the groundwater bank scenario than in the baseline scenario, this additional water is not enough to cover the difference in the storage for DR-025.

Resilience is the probability that a deficit period will be followed by a successful period during the simulation period (Hashimoto et al. 1982). Table 3 shows the resilience for the selected users and the treaty obligations. The results show an increase in the resilience for all of these entities. Groundwater banking promotes a more resilient system by using the groundwater in dry periods and letting the surface water increase rapidly, so the system recovers faster than under the baseline scenario. When a deficit occurs, the recovery is faster under the groundwater banking policy.

Vulnerability is the magnitude of water delivery deficits over the period of simulation as a percentage of the demand (Hashimoto et al. 1982). Table 3 shows the vulnerability (average deficit over the period of simulation as a percent of total demand) for the selected users and treaty obligations. The results show a decrease in vulnerability for DR-025, WMS 8-13, and the deliveries to the treaty obligations and a slight increase for DR-005. For DR-025, WMS 8-13, and the treaty, when deficits occur, they are smaller under the groundwater banking policy than the baseline scenario. For DR-005 there is a smaller probability that deficits will occur (higher reliability), but when they happen, they will be slightly larger (by 2% on average). During drought periods, DR-005 utilizes surface water, groundwater, and banked water to supply its requirements. Deficits occur when the bank is empty, and the other two sources are unable to satisfy the demand. Even though the bank helps supply water to DR-005 (improved reliability and resilience), the length and severity of droughts in the basin result in depletion of the banked water and increase the deficits.

Table 3 also shows the maximum annual deficit over the 60-year simulation period for both scenarios. The results show a decrease in the maximum deficit for DR-005 and WMS 8-13 (30 and 2%, respectively), a slight increase for DR-025, and no change for the treaty deliveries. For DR-025, the increase in the maximum deficit has the same reasons as the decrease in the reliability described above: during wet periods the storage in the reservoirs that supply DR-025 is lower and in dry periods, the extra outflow from the Rio Conchos is not enough to make up for the difference in the reservoir storage.

Sustainability indices have been used to summarize the three performance criteria discussed above (Loucks 1997; McMahon et al. 2006). We use a variation of the sustainability index proposed by Loucks (1997), the geometric average of reliability, resilience, and vulnerability. For the ith stakeholder we have

$$Sust_i = [Rel_i Res_i (1 - Vul_i)]^{1/3} \tag{7}$$

Table 3 shows the sustainability index values for the selected water users. The results show an increase in the sustainability index for all users and the treaty deliveries. This result means that, overall, the groundwater banking policy benefits all of the basin users considered as well as the treaty.

Treaty Obligations

One of the most important aspects of water management in the Rio Grande basin is the delivery of water from Mexico to the United States. In short, the required delivery is 431.7 million m^3/year averaged over a 5-year period. Fig. 4 shows the minimum, maximum, standard deviation, and median annual delivery for the six tributaries listed in the 1944 Treaty in terms of the percent delivery relative to the required average annual volume. Under the groundwater banking policy there is (1) no decrease in the minimum treaty delivery, which means no harm to water users downstream during drought periods; (2) a slight decrease in the median delivery (2%), which does not affect

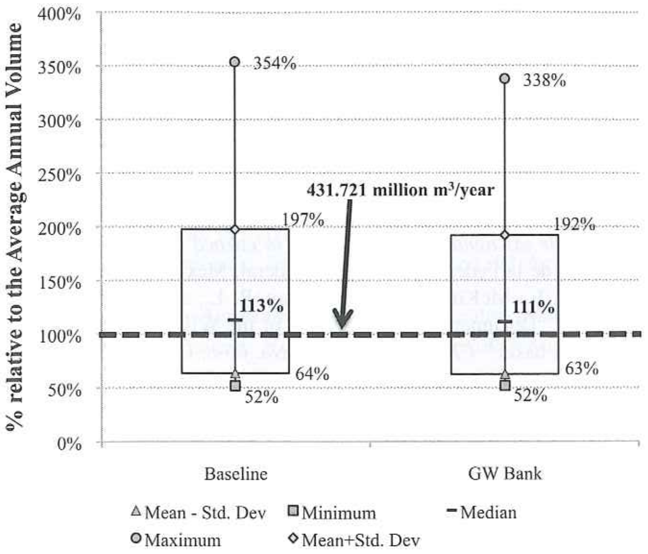


Fig. 4. Treaty deliveries for the six tributaries listed in the 1944 Treaty under the baseline scenario and groundwater banking scenario (GW bank)

the treaty obligations since the median is above the minimum required; (3) a decrease in the maximum delivery (16%), which indicates an improvement in basin management efficiency during wet periods, since the baseline maximum delivery is well above the requirement; and (4) a decrease in the standard deviation, indicating a reduction in the variability of treaty deliveries and a more stable delivery of water, which is preferable from a management point of view (Collado 2002; Teasley and McKinney 2005; CONAGUA 2007).

Table 3 shows the reliability, resilience, vulnerability, maximum deficit, and sustainability for the treaty deliveries over the 60-year period of simulation. Reliability and resilience for the treaty obligations do not change under the groundwater banking scenario compared to the baseline scenario. This means that the periods with deficit and the probability of recovering from a deficit are the same as in the baseline scenario. In contrast, the vulnerability, which is the average deficit, is 2% less in the groundwater banking scenario than in baseline scenario. The results show an increase in the sustainability index of 0.7%.

These results imply that the groundwater banking policy improves the ability of Mexico to comply with the treaty obligations and that this is physically feasible for the Rio Grande basin. The sustainability index results show that there are improved benefits for water users in the whole basin. There is a significant increase in reliability for irrigation district DR-005 Delicias, the average deficits (vulnerability) are decreased, and the ability to recover from a deficit (resilience) is improved for irrigation district DR-025 Bajo Rio Bravo in Mexico and WMS 8-13 in the United States.

In order to develop groundwater banking in the Rio Conchos basin, the water users of DR-005 and CONAGUA would need to execute an agreement to implement the groundwater bank in the Meoqui aquifer. For CONAGUA, benefits from this agreement would be an improvement in water management, and for the water users, benefits would include better long-term water supply. For the success of the groundwater bank, stakeholders would need to consider local water management, avoiding hydrologic risks, monitoring programs, dispute resolution, promotion of local benefits, and financial arrangements, among other characteristics (Thomas et al. 2001). For the specific case of hydrologic risks, pumping limits, maximum water table depletion, and locating wells so as not to affect third parties, among others, must be considered. In addition, it is necessary to install a monitoring system that tracks the water deposited to and extracted from the bank. It is important to include all of the Meoqui aquifer water users in the process and to respect the groundwater banking methodology. An intensive campaign of communication by the water authorities would need to be carried out to ensure the success of the policy. Further research on the hydraulics of the Meoqui aquifer needs to be carried out in order to validate the results discussed above. Another limitation is the naturalized flow data for recent periods (after September 2000). The TCEQ (2005b) and R. J. Brandes Company (2003) developed the naturalized flows from 1940 to 2000; however, since that time, no more naturalized flows have been added to the database by any agency from either country. It would be beneficial to have naturalized flows for the whole basin through 2007 since treaty cycle 27 finished then and the Mexican debt of water to the United States was paid, and the extended drought of the 1990s ended.

Regarding the treaty obligations, the benefits include a decrease in the average deficit (vulnerability) and in the variability of treaty deliveries. Water authorities responsible for implementing and monitoring the 1944 Treaty (i.e., IBWC-CILA) will experience less stakeholder pressure when dealing with deficit conditions because the deficits will be smaller than under current policies. Water authorities in charge of water allocation (i.e., TCEQ and CONAGUA) will have a more stable supply from the Rio Conchos, allowing a more reliable water allocation to water users along the Rio Grande.

Conclusions

In lieu groundwater banking has been presented here as an alternative water management policy that may improve water supply in water stressed basins. In order for this method to be applied, it is necessary to have a water user that is supplied by a combination of surface and groundwater. The method was tested on a case study in the Rio Grande basin. In lieu groundwater banking in the Meoqui aquifer in the Rio Conchos subbasin appears to be hydrologically feasible for improving the sustainability of water supplies into users in the basin (DR-005) and it does not diminish benefits enjoyed by other Rio Grande water users downstream in the United States or Mexico. There are wet periods when the irrigation district DR-005 demand can be supplied completely from surface water, allowing deposits to the bank by natural recharge, and there are drought periods when this banked water can be withdrawn to supply the irrigation district without harming other water users in the basin. The procedure to operate the aquifer and groundwater bank storage to account for the water stored and withdrawn from each account has been demonstrated here.

In the case presented here, in lieu groundwater banking improves the total system storage in the basin (an increase of 19%), mostly in the aquifer. Evaporative losses from reservoirs are reduced, and spills are less likely to occur. In addition, water supply to users is improved, reliability and resilience are increased, and vulnerability is decreased under normal and drought conditions. Mexican irrigation district DR-005 is the basin water user with the greatest benefit from this policy. Even though no water from the bank was delivered to users in the lower part of the Rio Grande basin (irrigation districts DR-025 and WMS 8-13), these users experienced small increases in their water supply under normal and drought conditions. Groundwater banking improves treaty deliveries from the Rio Conchos tributary. During drought periods, more water is delivered when it is most needed and during wet conditions, less water is delivered when it is less needed. In addition, treaty obligations are fulfilled more often, and the variability and vulnerability of the deliveries are reduced.

According to Mexican law, it is possible to establish a groundwater bank in the Meoqui aquifer, but it would have to be owned and operated by CONAGUA. The possibility of obtaining an extra amount of water from the bank during drought periods may encourage groundwater users to switch to this method. It would be important for CONAGUA to supervise and guarantee the proper operation of the groundwater bank according to the agreed method.

Further research is necessary to determine the hydraulic characteristics of the Meoqui aquifer such as hydraulic conductivity, storage capacity, unsaturated aquifer space, surface-groundwater interaction, and groundwater flow, among other characteristics. These data will provide detailed information to define the operation rules for deposits and withdrawals, restrictions, capacity, and limits of the groundwater bank proposed in this paper. The methodology presented in this paper assumes that the aquifer hosting the groundwater bank is completely disconnected from the surface water system; thus there are neither losses of groundwater to surface flow (i.e., due to springs or recharge to streams) nor to any groundwater flow outside the aquifer bounds. In practice, these assumptions may change and modifications to the policy must be required to account for losses in the aquifer system due to discharge to surface flow, springs, and/or groundwater flow to other aquifer systems. For instance, groundwater losses could be subtracted to the aquifer and bank account proportionally to the amount storages in each account. The analysis of the physical, geohydrological, and economical characteristics of the aquifer hosting the groundwater bank will redefine this policy for each particular case. This analysis will ultimately define the feasibility to implement the groundwater banking through the in lieu method.

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