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Sustainability Index for Water Resources Planning and Management

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Abstract:

This paper presents a *Water Resources Sustainability Index* that makes it possible to evaluate and compare different water management policies with respect to their sustainability. The Sustainability Index identifies policies that preserve or improve the desired water management characteristics of the basin in the future. This index is based on a previous sustainability index; with improvements in its structure, scale and content to make it more flexible and adjustable to the requirements of each water user, type of use and basin. The Rio Grande transboundary basin is used as a case study demonstrating the use of the index. Tailor made sustainability indices are defined for water users in Mexico, the US, the environment and for meeting system requirements (international treaty obligations). Group sustainability indices are calculated to summarize the results for groups of water users of each country, the environment and the basin as a whole. Sustainability indices by sub-basins are calculated to identify areas of potential improvement and regions at risk.

Keywords: Sustainability Index, Sustainable Policies, Adaptive Capacity, Water Resources, Rio Grande

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Introduction

It has been 30 years since the concept of "Sustainable development" was for the first time introduced by the World Conservation Strategy (IUCN 1980). Sustainable development balances the exploitation of the natural resources, technology development and institutional change, in order to enhance the potential to meet human needs and aspirations, now and in the future (WCED 1987). To achieve sustainability, all the components in the system must be also in balance. Loucks (1997) defined sustainable water resources systems as "those systems designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." While this concept is still valid, water management policies that promote sustainable water resources systems are becoming more difficult to identify because of environmental considerations, water scarcity and climate change.

Recent, strong emphasis has been placed on adaptive capacity of water resource systems, which refers to measures that reduce the vulnerability of systems to actual or expected future changes. Vulnerability is the magnitude of an adverse impact on a system. Thus, the objective is to look for policies that reduce the adverse impacts of actual and expected events; and to the extent possible, meet the water requirements for humans and the environment, now and in the future. To accomplish this goal it is necessary to have performance measures or indices that allow the evaluation and comparison of water resources systems under different scenarios. The objective of this paper is to present a *Water Resources Sustainability Index* which makes it possible to evaluate and compare alternative management policies for water resources systems.

The Sustainability Index (SI) summarizes the performance of alternative policies from the perspective of water users and the environment; it is also a measure of a system's adaptive

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capacity to reduce its vulnerability. If a proposed policy makes the system more sustainable the index will show that the system will have a larger adaptive capacity. The index proposed here is a variation of the sustainability index developed by Loucks (1997) with improvements in its structure, scale and content to make it more flexible and adjustable to the requirements of each basin. The SI is an integration of performance criteria that capture the essential and desired sustainable characteristics of the basin. The index facilitates comparison of policies when there are tradeoffs among performance criteria.

First, the performance criteria parameters used in the SI are described. Second, the SI for individuals and water user groups is defined. Third, water management in the Rio Grande basin, used as a case of study, is presented. Fourth, the SI for the current water management policy and three adaptation policies are defined for different groups of stakeholders in the Rio Grande basin. Finally, conclusions and recommendations are presented.

Performance Criteria

Performance criteria are used to evaluate water management policies and make possible the comparison of alternative policies. Performance criteria can be just simple averages, such as: system storage, water supply, evaporation, municipal shortfalls (average deficits), and outflow of water from a system (Vigerstol 2002). Probability based performance criteria include time-based (annual, monthly) and volumetric reliability (TCEQ 2007), resilience (Hashimoto *et al*. 1982),

Reliability

Water demand reliability is the probability that the available water supply meets the water demand during the period of simulation (Klemes *et al*. 1981; Hashimoto *et al*. 1982). For each time period, t, deficits, D_t^i, are positive when the water demand, $X^i_{Target,t}$, is bigger than the water

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supplied, $X^i_{Supplied,t}$, for the i^{th} water user; if the water supplied is equal to water demand ($X^i_{Supplied,t}=X^i_{Target,t}$), deficits are zero, $D^i_t=0$ (Loucks 1997).

$$D_t^i = \begin{cases} X^i_{Target,t} - X^i_{Supplied,t} & if\ X^i_{Target,t} > X^i_{Supplied,t} \\ 0 & if\ X^i_{Target} = X^i_{Supplied,t} \end{cases} \qquad [1]$$

Time based reliability, Rel^i, is considered, which is the portion of time that the water demand is fully supplied, *# of times* $D^i_t=0$, with respect to the number of time intervals considered, n, (e.g., months or years) (McMahon *et al.* 2006).

$$Rel^i = \frac{\#\ of\ times\ D_t^i=0}{n} \qquad [2]$$

Resilience

Resilience is a system's capacity to adapt to changing conditions (WHO 2009). Since climate conditions are no longer steady, resilience must be considered as a statistic that assesses the flexibility of water management policies to adapt to changing conditions. According to Hashimoto *et al.* (1982), resilience is the probability that a system recovers from a period of failure. Moy *et al.* (1986) used the maximum number of consecutive deficit periods prior to recovery as an alternative definition of resilience. Resilience, Res^i, is the probability that a successful period follows a failure period, (*# of times* $D^i_t=0$ *follows* $D^i_t>0$), for all failure periods, *# of times* $D^i_t>0$ *occurred*. This statistic assesses the recovery of the system once it has failed.

$$Res^i = \frac{\#\ of\ times\ D_t^i=0\ follows\ D_t^i>0}{\#\ of\ times\ D_t^i>0\ occurred} \qquad [3]$$

Vulnerability

Vulnerability is the likely value of deficits, if they occur (Hashimoto *et al.* 1982). Essentially, vulnerability expresses the severity of failures. Vulnerability can be expressed as: (1)

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the average failure (Loucks and van Beek 2005); (2) the average of maximum shortfalls over all continuous failure periods (Hashimoto *et al*. 1982; McMahon *et al.* 2006); and (3) the probability of exceedance of a certain deficit threshold (Mendoza *et al*. 1997). In this paper is used the first approach, the expected value of deficits, which is the sum of the deficits, D^i_t, divided by the deficit period, *# of times* $D^i_t>0$ *occurred*. Dimensionless vulnerability is used by dividing the average annual deficit by the annual water demand, *Water Demand*^{i}, for the i^{th} water user.

$$Vul^i = \frac{\left(\frac{\sum_{t=0}^{t=n} D_t^i}{\#\ of\ times\ D_t^i>0\ occurred}\right)}{Water\ Demand^i} \qquad [4]$$

Standard Deviation

The standard deviation of the water supply for the i^{th} water user in period t is

$$\sigma^i = \frac{\sqrt{\frac{\sum_{t=1}^{t=n}\left(X^i_{Supplied,t}-\bar{X}^i_{Supplied}\right)^2}{(n-1)}}}{Water\ Demand^i} \qquad [5]$$

where the average water supply, $\bar{X}^i_{Supplied}$, is:

$$\bar{X}^i_{Supplied} = \frac{1}{n}\sum_{t=1}^{t=n} X^i_{Supplied,t} \qquad [6]$$

This performance criterion (Hirsch 1979, Cai *et al*. 2002) indicates the variability of the water supply when part or all of a user's water demand is not supplied from controlled facilities, such as, unregulated rivers. A dimensionless standard deviation has been defined in Eq. 5 by dividing the volumetric standard deviation by the annual water demand, *Water Demand*^{i}.

Maximum Deficit

The maximum deficit, if deficits occur, is the worst-case annual deficit, $max(D^i_{Annual})$, for the i^{th} water user (Moy et al. 1986). A dimensionless maximum deficit is used by dividing the maximum annual deficit by the annual water demand, *Water Demand*^{i}.

$$MaxDef^{\,i} = \frac{\max(D^i_{Annual})}{Water\ Demand^i} \qquad [7]$$

Sustainability Index (SI)

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Indices represent aggregate measures of a combination of performance measures, or in other words, an index is a "synthesis of numerous factors into one given factor" (Sainz 1989). Several indexes have been developed for environmental processes such as the Environmental Index (Milbrink 1983), Environmental Stresses index (Reiquam 1971), Environmental Sustainability Index (Esty *et al*. 2005), the Multi-attributed Environmental Index (Hajkowicz 2005); and also some indices specifically for water resources, such as the Drought Risk Index (Zongxue *et al*. 1998), the Palmer Drought Severity Index (Palmer 1965), Water Quality Index (Brown *et al.* 1971), Fairness (Lence *et al*. 1977), Reversibility (Fanai and Burn 1997) and Consensus (Simonovic 1998).

In order to quantify the sustainability of water resources systems, Loucks (1997) proposed the SI, with the objective to facilitate the evaluation and comparison of water management policies. The SI is a summary index that measures the sustainability of water resources systems; it can be used to estimate the sustainability for water users and to obtain the change in sustainability by comparing the index among several water policies proposed. Frequently, indices are criticized because they are seen as a sum of disparate items (Hopkins 1991) and sometimes in practice; people in the water sector are reluctant to use indices (Brown *et al.* 1971). The SI summarizes essential performance parameters of water management in a meaningful manner, rather than adding broad factors and the SI has been used by the scientific community (Ray *et al.* 2010, McMahon *et al.* 2006, Loucks 1997).

Sustainability by User

Loucks (1997) proposed the following SI for the ith water user

$$SI^{i} = Rel^{i} * Res^{i} * (1 - Vul^{i}) \quad [8]$$

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The SI has the properties of: (1) its values vary from 0 to 1; (2) if one of the performance criteria is zero, the sustainability will be zero also; and (3) there is an implicit weighting, the index gives added weight to the criteria having the worst performance. The multiplicative form of the SI considers each criterion as essential and non-substitutable. Sagar and Najanm (1998) suggested this as the proper manner for integrating performance criteria. For instance, Reiquam (1971) used the multiplicative form for the Environmental Stresses index.

A variation of Loucks' SI is proposed here, with the index defined as a geometric average of M performance criteria (C^i_m) for the i^{th} water user

$$SI^i = \left[\prod_{m=1}^{M} C^i_m\right]^{1/M} \qquad [9]$$

For instance, if the performance criteria are $C^i_1 = Rel^i$, $C^i_2 = Res^i$, and $C^i_3 = 1\text{-}Vul^i$, the SI for the i^{th} water user is

$$SI^i = \left[Rel^i * Res^i * \left(1 - Vul^i\right)\right]^{1/3} \qquad [10]$$

This index satisfies the properties of the SI defined by Loucks (1997), but, in addition, has the following improvements:

Content – Allows the inclusion of other criteria of interest according to the necessities of each case. The SI is no longer a fixed performance criteria related to water quantity; performance criteria of water quality and environmental performance might be included in the SI. For instance, if the Total Dissolved Solids (TDS) of the water delivered to a user must be below a permitted value, the reliability for TDS not exceeding the desired threshold can be calculated and included in the SI. Notice that the criteria (C^i_m) included in Eq. 9 must have a scale from 0 to 1 and desirable criteria values tend to 1. Scaling and complements $1\text{-}C^i_m$ can be applied prior to including any performance criteria into Eq. 10.

Scaling – The use of the geometric average scales the values of the SI, generating numbers that can be more practical to interpret and communicate. Suppose that a certain water user has a reliability, resilience and vulnerability of 50% for each performance criterion. The SI calculated

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with the prior definition (Eq. 8) and the proposed index (Eq. 9) are 13% and 50%, respectively. The scaling of the SI does not obscure poor performance; its only purpose is to scale the values and make the index more practical and intuitive. In addition, more than 3 parameters can be included in the SI, the product of several factors will result in small numbers and without scaling, changes in the SI might be difficult to discern.

Flexibility – Several structures for the SI might be applied in the same basin for different groups of water users or types of use. For instance, SI for municipal or recreational water use may include different performance criteria than the SI for agriculture water use. Water quality and environmental performance criteria may be included for municipal and recreational water use, respectively, while the standard SI (Eq. 10) might be appropriate for agriculture use. Sustainability does not mean the same thing for all water users and the proposed index allows it to be adjusted to suit the user or use of water.

The improvements to the SI are not merely mathematical. The updated SI is a holistic approach to define the sustainability for each group of water user. The structure of the index incorporates tailor-made parameters that for some water users may be crucial in their water management; the scaling of the index allows a more intuitive result; and the flexibility to use different SI structures in the same system allows the meaningful discrimination of performance parameters for specific groups of water users.

Sustainability by Group (SG)

In order to compare groups of water users, the Sustainability by Group (SG) was defined as a weighted average of sustainability indices (Loucks 1997). The SG is used to calculate the sustainability for a group k with i^{th} to j^{th} water users belonging to this group.

$$SG^k = \sum_{i=1 \in k}^{i=j \in k} W^i * SI^i \quad [11]$$

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where W^i is a relative weight for the i^{th} water user, ranging from 0 to 1 and summing to 1. If the SI of each user is weighted by its annual water demand, the SG for the k^{th} group is expressed as

$$SG^k = \sum_{i=1\in k}^{i=j\in k} \frac{Water\ Demand^i}{Water\ Demand^k} * SI^i \quad [12]$$

where

$$Water\ Demand^k = \sum_{i=1\in k}^{i=j\in k} Water\ Demand^i \quad [13]$$

The relative importance of each variable is reflected in the weights. There are many weighting options, such as, (1) an arithmetic average or equal-attribute-based weighting system (Slottje 1991, Reiquam 1971); (2) explicit weights obtained through: (a) utility theory analysis (Loucks *et al*. 1997; Von Neumann and Morgenstern 1974), principal components analysis or hedonic model according to regression coefficients (Slottje 1991); or (b) weights defined by consultations with experts (Gwartney *et al*. 1996), decision makers (Vigerstol 2002) or researcher expertise (Giorgi and Mearns 2002). Weights of Eq. 12 obtained through the annual water demand are used in this paper considering that: (a) the necessities of the water users and the environment can be expressed in the water demand value; (b) interviews with authorities and water users agreed this formulation; and (c) other performance criteria of interest are functions of water demand value, and can be scaled (normalized) using it, i.e., vulnerability, maximum deficit and standard deviation. The authors considered that the water necessities for water users and the environment are expressed in their water demand. However, there are limitations when water demands have not yet been estimated, e.g. for the environment, or when the water demand provided by the authorities underestimates the water necessities for water users and the environment.

The Rio Grande Basin

The Rio Grande basin is a transboundary basin between the United States (US) and Mexico (Fig. 1.a). Due to its geographical position, it is one of the most stressed basins in the world (WWF 2007), not only due to the increase in water demand as a result of population and industry growth, but also because of the natural water scarcity in the region. Extended periods of

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drought (> 10 years), coupled with over-allocation of water rights, low efficiency in irrigation systems and international agreements, make the Rio Grande basin a highly complex water resources system.

Water Management Principles for the Rio Grande Basin

The Rio Grande basin is used to exemplify the proposed SI. Here, it is analyzed the middle and lower part of the basin, from Elephant Butte dam in New Mexico to the mouth at the Gulf of Mexico (Fig. 1.b). Water management of the basin results from four aspects: (1) international agreements; (2) Mexican water policies; (3) US water policies; and (4) the environment.

International Agreements: Treaty of 1944

The 1944 treaty between United States and Mexico specifies the water allocation for both countries (IBWC 1944) with a primary division of 6 tributaries originating in Mexico as one-third to the U.S. and two-thirds to Mexico. The third shall not be less than 431.721 million m^3/year as an average over cycles of 5 consecutive years. Two international dams (Amistad and Falcon) are used to store and manage the water for both countries and each country has its own storage account in each reservoir. The treaty cycles can expire in less than five years if the account of U.S. storage in both dams is filled with water. At the end of a 5-year cycle, the International Boundary and Water Commission (IBWC) evaluates the Mexican delivery of water to the U.S. and determines if the treaty obligations have been met. If there is a deficit in the treaty delivery, it must be paid in the following cycle (IBWC 1944).

The sustainability index proposed for the treaty obligations is

$$SI^{Treaty} = \left[Rel^{Treaty} * Res^{Treaty} * (1 - Vul^{Treaty}) * (1 - \sigma^{Treaty})\right]^{1/4} \quad [14]$$

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Four out of the six Mexican tributaries delivering water to the treaty are unregulated rivers (Arroyo Las Vacas, San Diego, San Rodrigo and Escondido). In addition, there is no defined policy in the other two, regulated rivers (Rio Conchos and Salado) to deliver water to meet treaty obligations. In practice, only the gains of the reach between the most downstream reservoir in each tributary and the Rio Grande confluence are left in the river to meet the treaty obligations. Sporadically, reservoir spills during the hurricane season contribute to the delivery of treaty obligations. Due to the uncontrolled nature of the treaty deliveries, the standard deviation criterion is included in the SI to assess treaty obligations and help identify adaptation policies that reduce the variability of deliveries, providing a more steady delivery of treaty water by increasing low flows during drought periods and reducing spills during wet periods. The standard deviation for the treaty obligations is calculated from the annual deliveries of the six Mexican tributaries.

Mexican Water Policy

Mexican water demands are characterized by use (CONAGUA 2004a). For this research, municipal, domestic and agricultural water users are considered, accounting for the 99.2% of the total Mexican water demand (CONAGUA 2004b). Municipal and domestic users have the highest priority and two times their annual water demand must be stored in the reservoirs. Water allocations to agricultural users are not guaranteed and their allocations depend on the available storage in the respective dams that supply them. Each October, CONAGUA (water authority in Mexico) 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.

The sustainability index proposed for Mexican water users is

$$SI^{MX\,i} = \left[Rel^{MX\,i} * Res^{MX\,i} * \left(1 - Vul^{MX\,i}\right) * \left(1 - MaxDef^{MX\,i}\right)\right]^{1/4} \quad [15]$$

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The Rio Grande is a naturally water scarce basin, extended and severe periods of drought have occurred in the basin. During the latest drought (1994-2003), Mexico was not able to deliver the treaty water to the U.S. in two consecutive cycles of the 1944 treaty: cycle 25 (1992-1997) and cycle 26 (1997-2002). In order to cover these deficits, extraordinary measures were taken by the authorities, such as stopping the supply for some Mexican irrigations districts and transferring Mexican storage in the international reservoirs to the U.S. These decisions severely affected Mexican agriculture water users in the basin, almost extinguishing this activity in the lower part of the basin. Because of this, the Maximum Deficit criterion is included in the SI for Mexican water users.

United States Water Policy

The Texas Rio Grande Watermaster Program represented by the TCEQ (water authority in Texas) regulates the US water diversion from Amistad reservoir to the Gulf of Mexico (TCEQ 2005) based on to the US storage provided by the IBWC. Each user has an account and water is allocated (TCEQ 2006) based on the water use (irrigation, municipal, mining, industrial and other) and the type of water right (Type A or B). Municipal and industrial users have the highest priority and they are guaranteed an amount for each year. Allocations to the other users are not guaranteed and depend on the water remaining in their accounts.

The sustainability index proposed for US water users is:

$$SI^{US\,i} = \left[Rel^{US\,i} * Res^{US\,i} * \left(1 - Vul^{US\,i}\right) * \left(1 - MaxDef^{US\,i}\right)\right]^{1/4} \quad [16]$$

Similar to Mexico, agricultural water users in the US suffered shortages during the last drought and so, the Maximum Deficit criterion is also included in the SI for US water users.

The Environment

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Environmental flows have not been considered an integral part of water management in the Rio Grande. Important environmental habitats such as the Big Bend State and National Park in the US, the Northern Chihuahuan desert, Maderas del Carmen, Ocampo and Cañon de Santa Elena natural reserves in Mexico are ecologically threatened because of the lack of environmental water management policies. Historically, the basin has been manipulated in an exclusive human water resource management mode (Enriquez-Coyro 1976), not considering the environmental needs of the native ecosystems.

Several efforts have been undertaken to determine environmental flows needed in the basin (Sandoval-Solis and McKinney 2009). As part of an environmental flow assessment for the Rio Conchos, environmental flows were estimated at 9 locations (Fig. 1.c) (WWF 2006). A monthly variation for two conditions, maintenance or drought, was determined for each location. These flows are used to evaluate the performance of the environmental requirements. The sustainability index proposed for the environmental flows is:

$$SI^{Env\,i} = \left[Rel^{Env\,i} * Res^{Env\,i} * \left(1 - Vul^{Env\,i}\right) * \left(1 - MaxDef^{Env\,i}\right)\right]^{1/4} \qquad [17]$$

Simulation Model of the Rio Grande Basin

To illustrate the use of the new SI, several scenarios of water management in the Rio Grande basin are evaluated. Water resource allocation in the Rio Grande basin has been simulated using the Water Evaluation And Planning System (WEAP) software (Danner *et al.*, 2006). The allocation logic represented in the model follows the allocation of water for Mexico (CONAGUA 2004a), Texas (TCEQ 2006) and the international allocation of water established in the Convention of 1906 (IBWC 1906) and the Treaty of 1944 (IBWC 1944). Data for naturalized flows, conveyance losses, reservoir capacities, evaporation, among other variables were provided by CONAGUA and TCEQ and the IBWC (Danner *et al*. 2006). For the US, 100% water demand

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is taken as the full allocation water right established by the TCEQ in the Water Availability program (TCEQ 2006). For Mexico, 100% demand is taken as the volume declared by CONAGUA in 2004 (CONAGUA 2004b). Table 1 shows the water demands for each country. Monthly use coefficients are used to account for the seasonal variability for each demand. The period of analysis for the modeling is 60 years, using as input the naturalized streamflows from October 1940 to September 2000. The Rio Grande model has been calibrated and validated using a 24-year period (1976-2000) on which both international reservoirs (Amistad and Falcon) were in existence; in addition, the historic records of water diversions were available for this period. The simulation process considered the repetition of the 60 year hydrologic period with the recent infrastructure and demands in the basin.

Sustainability Index Use

In complex, stressed and shared water resources systems, such as the Rio Grande, it can be difficult to identify policies that improve water management. This section illustrates how the SI and SG can help identify which policies improve water management, for whom, where and by how much. The SI and SG are comprehensive tools integrating multiple performance measures that facilitate the evaluation and comparison of different water management policies.

By water user

To demonstrate the use of the proposed SI, two scenarios are compared systematically, a *Baseline* scenario that represents current water management policies in the basin and an *Alternative* scenario. The alternative scenarios represent policies that improve the efficiency of the system through water conservation measures, policies whose objectives are to reduce the use and/or consumption of water. In this section alternative scenarios are analyzed where water demand is reduced below the Baseline demand due to water conservation measures.

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In the first alternative, Scenario A, water conservation measures are implemented in irrigation district "005 Delicias" (DR-005), the biggest water user on the Mexican side with a demand of 942 million m^3/year. In Scenario A the water demand is progressively reduced from 100% to 20%, relative to the Baseline scenario demand. Fig. 2 shows the results for DR-005 according to Eq. 15. Results show that as demand is reduced: (a) the reliability increases; (b) the vulnerability decreases; (c) the resilience increases; (d) the maximum deficit does not decrease; and (e) the SI increases after a reduction to 70%.

Are there any benefits in Scenario A? If so, are they immediate when the water demand is reduced or are they delayed? By how much? The performance criteria do not allow us to answer these questions, but the SI does. For instance, for a 50% reduction in DR-005 water demand, results of reliability, resilience, vulnerability, maximum deficit and SI are 83%, 40%, 51%, 98% and 22%, respectively. In contrast, for a 40% reduction in DR-005 water demand, results for the same performance criteria are 78%, 23%, 45%, 96% and 24%, respectively. Using the performance criteria it is difficult to discern if the 10% water demand reduction improved the water management; however, the SI shows an increase of 2%. In addition, the water supply for DR-005 is not sustainable; one of the characteristics required for its sustainability (Eq. 15) is a reduction in the maximum deficit and in both scenarios is almost 100%. Although the reliability, resilience and vulnerability improve, the demand reduction proposed in Scenario A does not solve the problem of high maximum deficit. In Scenario A, there is almost no improvement until the demands is reduced to 70%; after this point, the water supply starts improving.

Two water conservation measures have already been implemented in the Rio Grande basin, specifically in DR-005 Delicias: (1) the permanent buyback of water rights through the Mexican PADUA program (SAGARPA 2003); and (2) improvements in the infrastructure to reduce conveyance losses and increase application efficiency through 1944 Treaty - Minute 309 (IBWC 2003). The result of both programs has been a savings of 366 million m^3/year (39%); 10% in PADUA, and 29% in Minute 309. Even though water demand has been reduced to 61% (575

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million m^3/year); the maximum deficit problem is not solved. The risk of experiencing a high deficit (Max. Deficit = 99%) is still imminent; this risk may leave farmers without any income for at least one year. Adaptive policies that promote conjunctive use of surface and groundwater, such as groundwater banking proposed by Sandoval-Solis *et al*. (2010), may reduce the risk of high deficits in DR-005.

Since there is no policy to allocate water to the environment, let's consider a hypothetical case where the water saved in Scenario A is used to meet the environmental needs for the Rio Conchos sub-basin. For purpose of brevity, only the results for control point VMc Camargo are presented because this point has the worst performance in the Baseline scenario. Fig. 3 shows the results according to Eq. 17. Results show that as water demand is reduced: (a) the reliability and resilience increase; (b) the vulnerability and the maximum deficit decrease; and (c) the environmental sustainability for this control point improves significantly.

In Scenario A, when the water demand of DR-005 is reduced from 100% to 90% and the water savings are used for environmental purposes, the SI for the environment grows 33%, from 24% to 57%. The SI becomes steady at 60%, meaning that Scenario A will be effective up to a 40% reduction in DR-005 demand, after this, no environmental benefits will be gained with this policy and other adaptive policies should be used to further improve the environmental conditions. Under the Baseline scenario, low reliability and resilience, and high vulnerability and maximum deficit are expected for the environment (100% demand); thus, under the current policies environmental sustainability is threatened.

Scenario B evaluates the water demand reduction of the user "Water Master Sections 8-13 Agriculture A" in Texas (WMS), the largest water user group on the U.S. side with a demand of 1801 million m^3/year. In Scenario B, WMS demand is reduced progressively from 100% to 40%. Fig. 4 shows the results according to Eq. 16. As water demand is reduced: (a) the reliability increase; (b) the resilience does not change until demand reaches a 50% reduction, after this point

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posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

it increases quickly; (c) the vulnerability and the maximum deficit decrease; and (d) the sustainability improves. The SI shows that Scenario B is beneficial for WMS.

During the last drought (1994-2003) the water supply for the US was compromised. At the beginning of the drought (1994-1996) the water supply for WMS was 78% (1400 million m^3/year) on average, for the rest of the drought (1997-2004) the water supply was 53% (950 million m^3/year) on average of the full allocation demand. This uncertainty in the water supply provoked the 75th Texas Legislature to order a study (Brandes 2004) that defined the water availability and the water use limits and vulnerabilities of the system. As a result, the "Current Allocation" for US water users other than municipal, domestic and industrial was set at 70% of the full allocation demand (TCEQ 2007) and this has been further reduced to 62% (personal communication, Carlos Rubenstein, Commissioner, TCEQ, October 2009). These decisions can be quantified by the SI, for 70% and 62% of the full demand the SI are 34% and 40%, respectively. Thus, reducing the water allocation from 70% to 62% represents a 6% benefit in the water allocation for WMS.

In stressed basins, such as the Rio Grande, adjustments in water management policy represent changes in the water allocation for stakeholders. Let's analyze the effects of Scenario B on the treaty obligations. Fig. 5 shows the results for the treaty obligations according to Eq. 14. Reducing the WMS demand will result in: (a) no change in the severity of the deficits (vulnerability) and in the variability of the deliveries (Standard Deviation); (b) an increase in the time the treaty obligations will be met (reliability); and (c) an increase in the recovery of the system (resilience). The SI shows that the treaty obligations will benefit as a result of Scenario B.

The 1944 Treaty specifies that Mexico must deliver to the U.S. a specified amount of water (2159 Million m^3) during a 5 year cycle; however, the cycles may expire earlier (less than 5 years) if the US storage capacity in both international reservoirs is filled. In Scenario B, the WMS demand is progressively reduced; therefore, less water is called for from the reservoirs and as a result, the U.S. storage capacity in the international reservoirs is filled more frequently. Thus, the period of time the treaty obligations are met (reliability) is greater than the Baseline scenario, and

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

if a deficit happens, the system recovers faster because it is more likely that the deficit can be made up with delivery from the 6 tributaries, or by filling the US storage capacity. The SI shows that the treaty obligation improves under Scenario B. These results are important because they show that fulfilling the treaty obligations is not only a function of the water delivered by Mexico, but also of the water demand in the U.S.

Sustainability By Group

Each water user has a unique SI that depends on the structure defined for the specific water management group to which it belongs (United States, Mexico, environment or treaty obligations). Because there are thousands of water users in the basin, and thus the same number of SI's, the Sustainability by Group (SG), shown in Eq. 12, is used to further summarize the results. Through this method it is possible to: (1) evaluate each water user according to required performance criteria defined for the management group to which it belongs; (2) summarize its performance by using the SI; and (3) summarize the performance of groups of water users by using the SG.

Table 2 shows the SG for five water user groups: (1) in the U.S.; (2) in Mexico with treaty obligations; (3) the environment in the Rio Conchos; (4) treaty obligations; and (5) all water users in the Rio Grande basin (including the environment and treaty obligations). Two scenarios are compared, the Baseline scenario and Scenario C, which is a combination of Scenarios A and B. Scenario C considers the water demand for WMS at 62% of the full allocation (current policy), for DR-005 at 61% of the full allocation (demand after buy-backs and water conservation measures), and that the water savings in DR-005 are used for environmental flows.

Because of the reduction in the WMS water demand, the sustainability of the treaty obligations and the U.S. group increased by 19% and 11%, respectively. Similarly, the sustainability for Mexico and the environment increased 16% and 8%, respectively, because of the reduction in the water demand of DR-005 and the delivery of the saved water to the environment.

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

Overall, the sustainability for the Rio Grande increased 15% with the adaptive strategies proposed in Scenario C.

In addition, water users have been grouped according to their location in the basin, using Eq. 12, in order to identify stressed water resource areas. Fig. 6 shows the SG of the *Baseline* scenario for 12 geographic areas, 5 in the U.S. and 7 in Mexico. For the U.S., the Forgotten River (US-1), Pecos (US-2) and the Lower Rio Grande Valley (US-5) sub-basins are the areas with the lowest sustainability. For Mexico, the Forgotten River (MX-1), Rio Conchos (MX-2) and Bajo Rio Bravo (MX-7) sub-basins are the areas with the lowest sustainability.

Along the border, three areas are of particular interest because of their complex water management: the Forgotten River (US-1/MX-1), the Big Bend area (US-3/MX-3), and the Lower Rio Grande Valley (US-5/MX-7). The Forgotten River sub-basin (US-1/MX-1) is the most stressed area in the basin, the growing water demand for municipal and industrial use in El Paso-Cd. Juarez plus the agricultural use of El Paso Water Irrigation District #1 (EPWID #1) and DR-009 Valle de Juarez have exhausted the water resources in the area; the water demands are larger than the natural availability of water in this area. These conditions are indicated in the results with a sustainability of 0%. For Mexican demands in this reach, the reliability is 0%, meaning that during the simulation period there was never enough water to meet their water demand; demonstrating the over-allocation of water rights. For US demands in this reach, in at least one year they experienced a deficit of 100%, so the maximum deficit criterion (1-Max Def) was never met, demonstrating the stress of the system. After the Forgotten River, the Lower Rio Grande Valley (US-5/MX-7) is the most stressed area in the basin; water supply in this region depends on the water use in the whole basin. Water management in the tributaries consumes the water that is produced before it reaches the Rio Grande main stream. The water supply of the Lower Rio Grande Valley depends on the storage of the international reservoirs, which depend on the water from the tributaries. During drought periods, almost no water flows to the Rio Grande from the tributaries, storage in both international reservoirs is greatly decreased and the water supply for

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

this area is threatened. The sustainability for MX-7 and US-5 are 18% and 34%, respectively. The Big Bend region (US-3/MX-3) is another stressed area. Even though the sustainability is 100%, this calculation does not consider the environmental needs for this region; the environmental flows for the Big Bend have not been defined yet. This result exemplifies a limitation of the SI and SG; when the water demand has not been calculated, e.g., for environmental flows in the big bend reach where water demands for other purposes are low, it is not possible to estimate the SI and as a result, the SG does not consider this water demand. In addition, most of the water in the Big Bend area comes from the Rio Conchos (75% on average) and is managed by CONAGUA without a defined policy to deliver water from the Rio Conchos to the Rio Grande. An international team has been working to define the environmental flows along this reach (WWF 2006; Sandoval-Solis and McKinney 2009); as well as a policy to provide environmental flows to the Big Bend reach.

Fig. 7 shows the increment in the sustainability (Δ Sust.) due to Scenario C. In the U.S., two regions benefit: Amistad-Falcon (US-4) and Lower Rio Grande Valley (US-5). In Mexico, three regions benefit: Rio Conchos (MX-2), Amistad-Falcon (MX-5) and Bajo Rio Bravo (MX-7) sub-basins. The geographic display of results allows us to identify: (a) regions at risk; and (b) regions that will benefit from an alternative water management policy.

Conclusions

The extent to which water management policies are sustainable can be determined using the SI proposed in this paper. The SI identifies policies that preserve or improve the desired water management characteristics of the basin in the future. The SI makes it easier to evaluate, compare and identify adaptive policies that improve water management when tradeoffs among performance criteria occur. The comparison of the SI among different policies allows identifying: a) if a policy is working, i.e., in scenario A, despite the efforts to improve the water supply of DR-005 by reducing its water demand the SI shows that its water supply is still unsustainable because the maximum deficit problem has not been solved; b) when a policy starts working, i.e., in scenario A the policy starts working after the water demand of DR-005 has been reduced to 70%; c) by how much the policy improves the water management, i.e., in scenario A the SI for VMc Camargo increases 33% when the water demand of DR-005 is reduced from 100% to 90% and the savings are allocated to the environment; d) at point a policy becomes useful, i.e., in scenario A the SI for VMc Camargo become steady at 60%, meaning that this policy is effective up to a 40% reduction in DR-005 demand; and e) if it affects other water users, i.e., the SI shows that scenario B also benefits the treaty obligations. The SI promotes a holistic water management evaluation because incorporates tailor-made performance criteria in the index structure and uses different structures in the same system. The SI is versatile; it was successfully applied to water users, environmental and system requirements.

The SG was successfully implemented to summarize the individual SI calculated for each water user, environmental or system requirements. Similarly to the SI, the SG make easier to evaluate, compare and identify adaptive policies that improve water management for groups of water users. The SG is versatile; groups of water users can be integrated according to the type of use (agriculture, municipal, environment), jurisdiction (United States, Mexico) or sub-basin. The comparison of the SG among different policies allows identifying which group of water users benefits and by how much, with respect to the reference scenario. By grouping water user according to their location, the SG makes it possible to identify regions that are at risk from unsustainable water management policies and regions that will benefit from an alternative water management policy. Determining weights for the SG through the annual water demand is used in this paper as an alternative method when explicit weights for water users, system requirements and the environment are not defined.

The SI and SG have been presented to decision makers in the basin who have recognized the practicality of the index. On one hand, the SI synthesizes the performance criteria that otherwise are tedious to analyze. On the other hand, SG is more convenient to compare the performance of groups of water users, and regions at a glance.

Recommendations

The SI is not intended to replace any performance criteria (i.e. reliability, resilience, vulnerability, etc.); its objective is to make easier the quantification and identification of policies that improve water management when there are tradeoffs between criteria. The SI can be included as one of the water management goals when decisions are being made regarding the design, planning and operation policies of water resource systems.

The methodology proposed in this article help identify policies that are more sustainable than a policy used as a reference (i.e., Baseline scenario) given the performance criteria considered for each water management group and the weights used in the SG. One drawback of the methodology proposed is the involvement of subjective judgment during the selection of performance criteria for the SI and weights for the SG.

In the simulation process, further research is needed to estimate and evaluate water management of the basin under different hydrologic conditions, considering the alteration of the hydrological cycle due to climate change. Also, in this research water demands are considered fixed for the hydrologic period of analysis. Further research is needed to estimate future demands and their evaluation in the planning simulation model.

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List of Figures

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010;
posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

List of Tables

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

Table 1. Water demands considered in the Rio Grande WEAP model

Water Use	Demands	Mexico	United States
Municipal	Number	21	23
	(Million m^3/year)	731	283*
Irrigation	Number	39	53
	(Million m^3/year)	3,881	3,034*
Other	Number	1	20
	(Million m^3/year)	47	11*
Groundwater	Number	35	21
	(Million m^3/year)	1,852	2,840**
Total	Number	96	120
	(Million m^3/year)	6,511	6,168

* Full allocation demand for U.S. water demands. The current allocation is 70% of the Full allocation

** This value represents an upper bound on aquifer withdrawal by these water demands

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

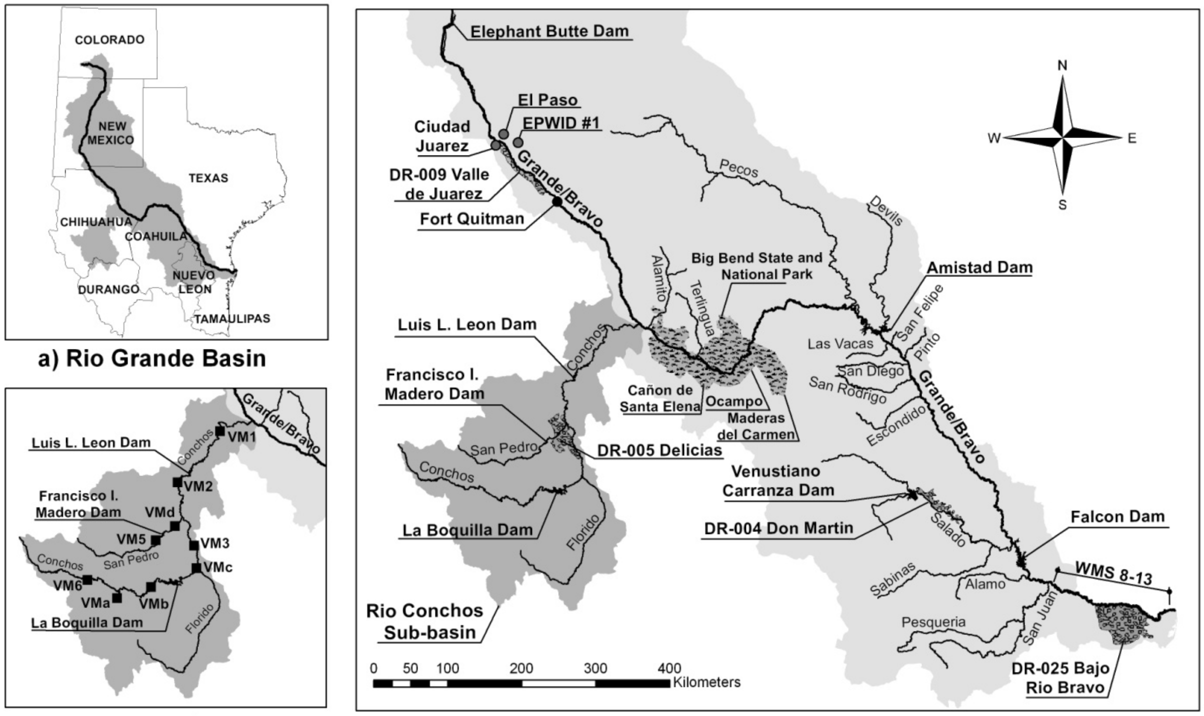
Table 2. Sustainability by Group, Baseline and Scenario C

	Sustainability		
Group	Baseline (%)	Scenario C (%)	Δ (%)
U.S.	30	41	+11
Mexico	33	49	+16
Treaty Obligations	51	70	+19
Environment	62	70	+8
Rio Grande	32	47	+15

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

List of Figures

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134



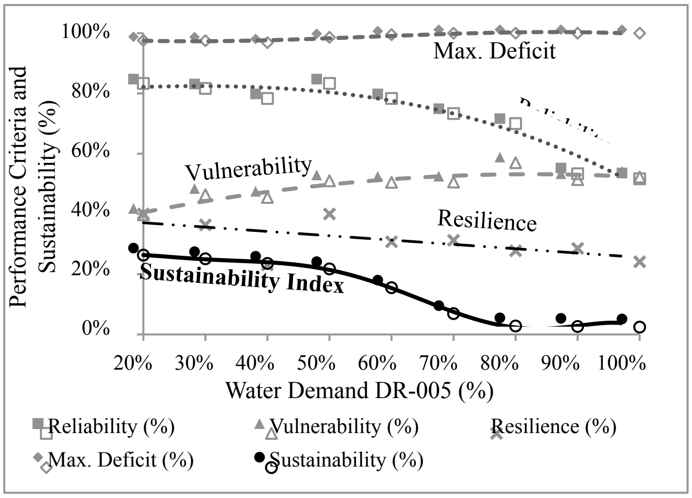
a) Rio Grande Basin

b) Hydrography Rio Grande Basin

c) Environmental Control Points

Fig 2.pdf

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134



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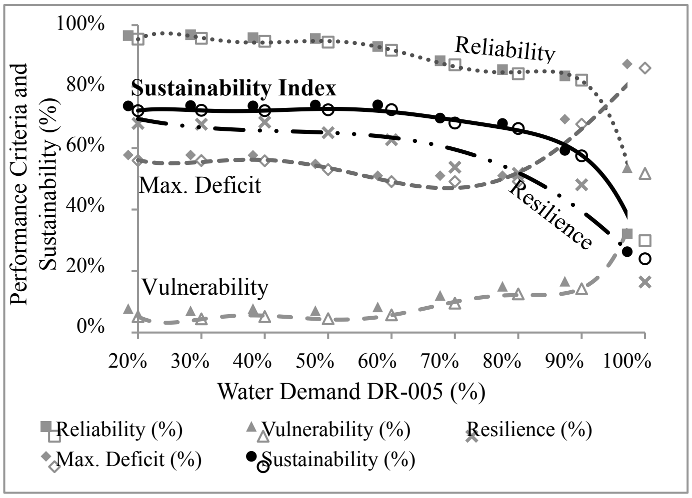


Fig 4.pdf

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

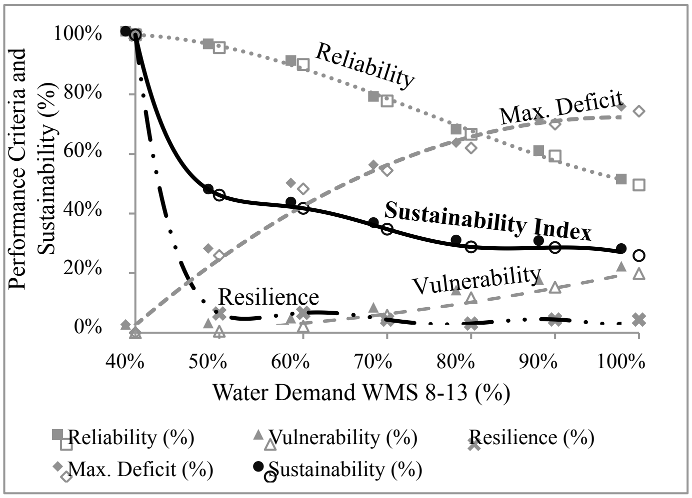


Fig 5 pdf

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134

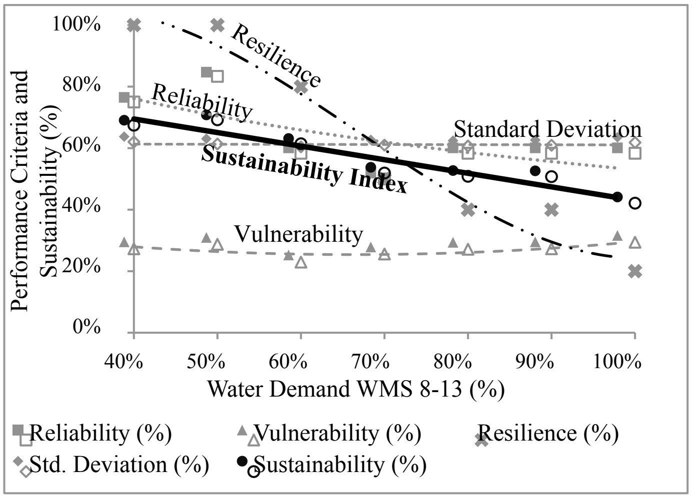
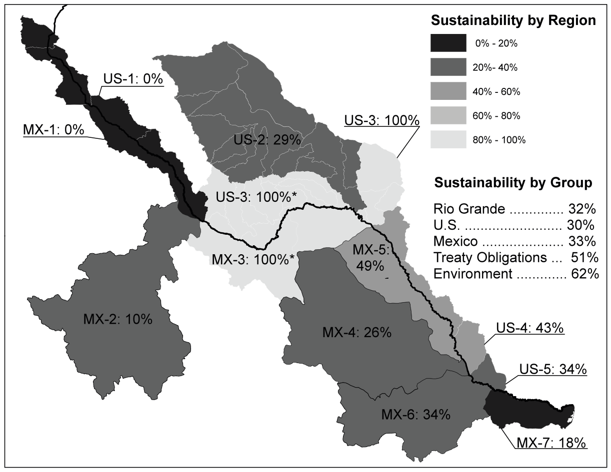


Fig 6.pdf

Journal of Water Resources Planning and Management. Submitted March 27, 2010; accepted October 21, 2010; posted ahead of print October 26, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000134



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