Assessment of relative impact of reservoir location

Tae Jin Kim

ABSTRACT

Reallocation of reservoir storage capacity for different water use purposes is regarded as one of the representative strategies for supplying water for human and environmental needs under the difficult situation of new reservoir construction. However, there are impacts of reservoir storage reallocation on river/reservoir systems because each reservoir in a multiple reservoir system is operated by priority order, not by natural order. Accordingly, this study focuses on evaluating the relative impact of reservoir location on a system of 14 multiple-purpose reservoirs and hydrology characteristics modification. The natural and priority orders are considered for three reallocation strategies. The comparison results of reliability, flood frequency, and economic flood damage indicate that individual reservoir storage reallocation has an impact on nearby reservoirs and river systems at downstream points, which are located directly below the reservoir. The multiple reservoir storage reallocation plans are reliable strategies for lessening the impacts on river/reservoir operating systems.

Key words | reservoir storage reallocation, water availability model, water rights, Water Rights Analysis Package (WRAP) model

Tae Jin Kim
Department of Civil Engineering,
Daegu University,
201 Daegudae-ro, Jillyang,
Gyeongsan,
Gyeongbuk, 712-714,
Korea
E-mail: *kimtj@daegu.ac.kr*

INTRODUCTION

Urbanization requires more unappropriated flows used for drinking water and other purposes, but the flows are limited and most of the flows are eventually converted into sea water during short duration times. Also, climate change derived from urbanization increases the possibility of the frequent occurrences of extreme events, i.e., floods and droughts. Accordingly, many studies have been focused on the construction of water supply systems, i.e., reservoirs, which have provided water to urban areas and controlled extreme events since 1900, in order to maximize the available water, and to minimize the risk of extreme events. However, with the constraints on environment, esthetics, and budget in developed countries, new reservoir construction has transitioned to optimize the use of limited available water resources since the 1970s. Modification of reservoir operation rules and reservoir storage reallocation in single reservoir/multiple reservoir systems have also been considered as alternative methods for increasing water availability for increased demands, providing water for environmental needs, and reducing the risk of threat to human life. However, these potential strategies have impacts on the aquatic life at the downstream location and other reservoir operating rules that are located above or below the modified reservoir. Accordingly, the selection of one, or more than one, reservoir for performing these strategies should be determined based on different evaluation criteria.

Most reservoir storage reallocation studies have focused on the evaluation of impact between each purpose. For example, studies have been performed that evaluate the reallocation of reservoir storage (Johnson *et al.* 1990) from hydropower to municipal and industrial water supply (Simonovic & Qomariyah 1993; McMahon & Farmer 2004), and from flood control to conservation pool (Wood *et al.* 1997; TWDB 2006). Economic analysis methods are proposed for evaluating the reallocation plan (Wurbs & Cabezas-Canelos 1987; Ford 1990; Babel *et al.* 2005). Reservoir system operation reviews (Labadie 2004; Wurbs 2005a; Rani & Moreira 2010) have been studied while considering several factors, including seasonal characteristics (Wurbs & Carriere 1993), mitigation flood damage during water supply operations (Craney 1996),

doi: 10.2166/aqua.2013.068

drought (Booker 1995), ecological impacts and water supply yields (Maddock *et al.* 2001), and irrigation (George *et al.* 2004). Recently, Kim (2012) has evaluated the impact of instream flow on municipal and irrigation water uses under three kinds of conditions, which are pre-dam construction, post-dam construction, and reservoir storage reallocation. These studies have been performed to investigate the purpose relationship of each reservoir in a specified operating system when one, or more than one, reservoir storage is reallocated. However, the studies do not provide the criteria for selecting and determining the reservoir that has little impact on water supply, environmental needs, and damage at the downstream area located in a multiple-purpose reservoir system.

The objective of this study is to assess the relative impact of reservoir location on other reservoirs' storage located in a particular river/reservoir system when one or more reservoir's storage is reallocated under priority, and natural-based, water allocation systems (Kim 2011) that increase the reliability for water use purposes of the conservation pool, and minimize the change of flood storage frequency and flood damage at downstream points below the dam. Three cases' application for individual, tributary, and all reservoir reallocations lead to the understanding of the relative impact and provide the selection guidelines for reasonable reservoir storage reallocation plans. The detailed information of the application is as follows. First, an individual reservoir that has flood control storage is reallocated based on the US Army Corps of Engineers (USACE) criteria (15% or 50,000 ac-ft) to evaluate the impact relationship of each reservoir. Second, multiple reservoirs located in the same river tributary are simulated simultaneously. Third, all reservoirs that have flood control storage in all watersheds are simulated simultaneously.

BRAZOS RIVER BASIN, DATASET AND MODEL

The Brazos River Basin has a total area of 115,565 km^2 and is shown in Figure 1. The average annual temperature varies from 16 °C in the high plains to 21 °C in the Gulf Marshes and Prairies. The mean annual precipitation varies from 483 mm in the upper basin which lies in the High Plains, to 1,143 mm in the lower basin in the Gulf Coast region (Wurbs & Kim 2008). The Brazos River Authority Condensed (BRAC) dataset (Kim & Wurbs 2011a) consisting of 14 reservoirs (Table 1 and Figure 2) with 1900–2007 hydrologic period-of-analysis periods (Wurbs & Kim 2011; Kim & Wurbs 2011b), and the Water Rights Analysis Package (WRAP) simulation model, one component of the Texas Water Availability Model (WAM) System (Wurbs 2005b, 2012a, b), that has been expanded with a daily time step model (Kim & Wurbs 2011c; Wurbs & Hoffpauir 2012), were utilized in this study.

Monthly water use distribution factors (Figure 3) and year 2000 conditions of reservoir sedimentation (Wurbs 2005b; TCEQ 2012) are assumed as the existing reservoir storage condition. The reservoir storage reallocation amount, based on USACE criteria (the lesser amount of 61.7 million m^3 or 15%), and projected future water use at year 2040 (HDR 2006) are utilized. Although the data are outdated, maximum allowable discharges (Table 2) at five control points, utilized by Wurbs & Carriere (1988), are used due to the difficulty of estimating new maximum allowable discharges. The discharge–damage curve for four index locations, including BRHB42, CON111, CON147, and BRRI70 as shown in Figures 1 and 2, were obtained from the Corps of Engineers. These relationships are based on field studies conducted during the 1960s in conjunction with planning for the construction of projects (Wurbs & Cabezas-Canelos 1987). Consequently, the estimates of damage susceptibility are outdated and very approximate, but are still considered adequate as indices for the purposes of the present study.

EVALUATION INDEXES

The following indices are utilized in this study: (1) reliability, (2) flood frequency analyses of annual peak reservoir storage, and (3) economic flood damage.

Volume reliability (R_v) is the percentage of the total target demand amount that is actually supplied. Period reliability (R_p) represents the likelihood or probability of the target being met in any randomly selected month or year (Wurbs 2012a).

$$R_v = \frac{v}{V} \times 100(\%) \tag{1}$$

$$R_p = \frac{n}{N} \times 100(\%) \tag{2}$$

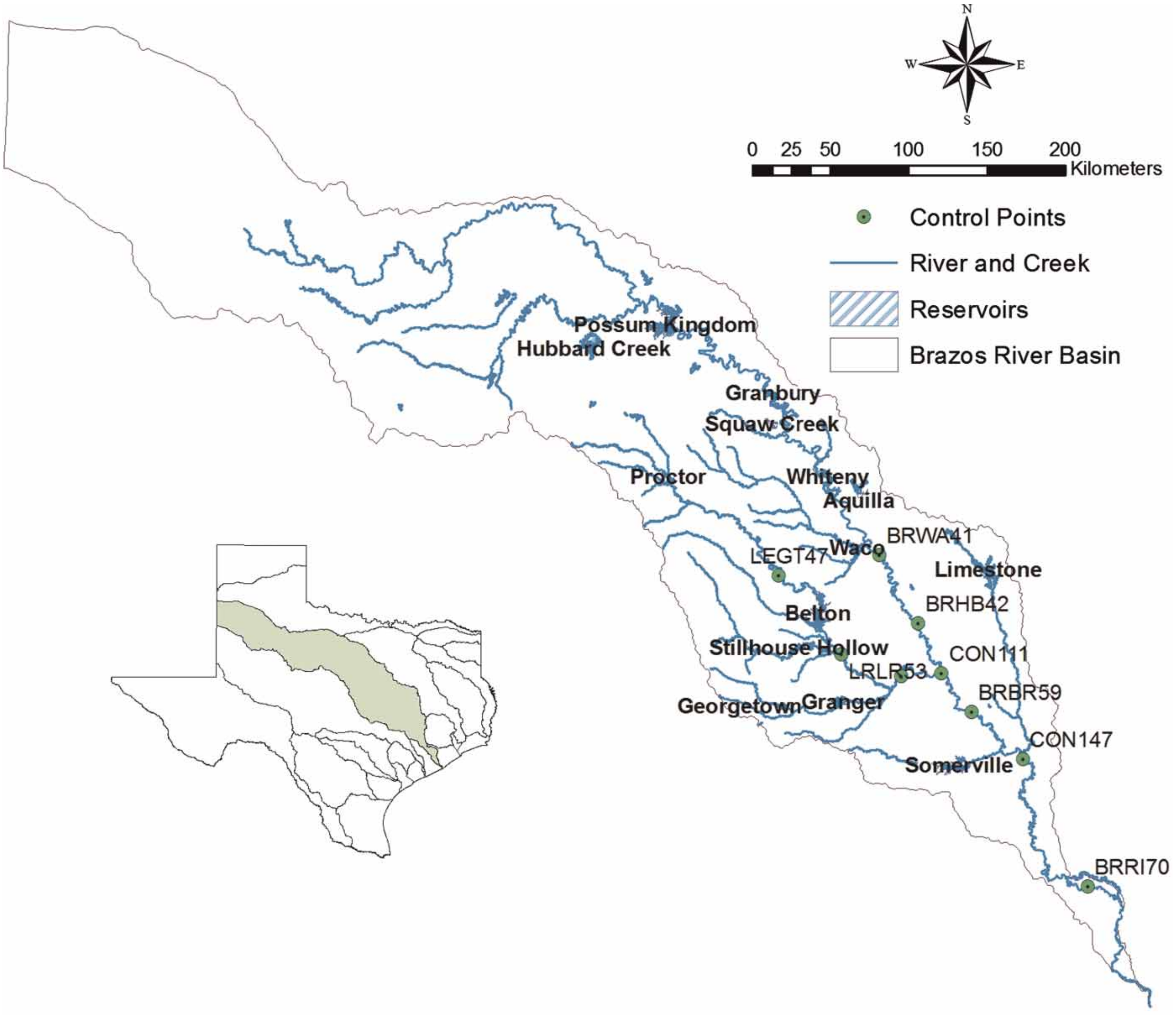

Figure 1 | Fourteen reservoir and nine control points considered in the Brazos River Basin, Texas.

where v is the volume supplied, V is the volume target. n is the number of periods during the simulations for which the specified percentages of the demand target is met, and N is the total number of periods.

The flood frequency analysis computations are based on applying the log-Pearson type III probability distribution. The random variable X is the maximum daily flow and end-of-period reservoir storage volume that occur in a year. The X corresponding to a given exceedance probability is determined from Equation (3), and combined with the frequency factor K, to exceedance probability P, and skew coefficient G.

$$\log X = \overline{\log X} + KS_{\log X} \tag{3}$$

The mean $\overline{\log X}$, standard deviation $S_{\log X}$, and skew coefficient $G_{\log X}$ of the logarithms of X are computed from an annual series of maximum daily flow or storage volumes X.

The frequency factor K is obtained as a function of the annual exceedance probability (P) and $G_{\log X}$ by linear interpolation of a Pearson type III probability table. The skew coefficient G is particularly sensitive to extreme

Table 1 | Multi-purpose reservoirs considered in this study

Reservoir name	Reservoir ID	Storage capacity Conservation pool (10^6 m^3)	Flood pool (10^6 m^3)	Total pool (10^6 m^3)	Amount of reallocation (10^6 m^3)	Total diversion (10^6 m^3/year)
Hubbard Creek	Hubbrd	392	–	392	–	12
Squaw Creek	Sqwcrk	187	–	187	–	22
Possum Kingdom	Possum	894	–	894	–	73
Granbury	Grnbry	191	–	191	–	44
Aquilla	Aquila	65	113	178	17	3
Waco	Lkwaco	255	566	820	–	47
Proctor	Prctor	73	492	565	–	17
Belton	Belton	564	1,859	2,424	62	133
Stillhouse Hollow	Stlhse	291	999	1,290	62	84
Georgetown	Grgtwn	46	219	264	17	15
Granger	Grnger	81	583	664	32	3
Somerville	Smrvle	197	806	1,004	62	59
Limestone	Lmstne	268	–	268	–	49
Whitney	Whitny	785	1,121	1,905	–	23
Total		4,289	6,758	11,047	251	584

flood events due to the cube term. Estimates from small samples may be inaccurate. Thus, Bulletin 17B of the Interagency Advisory Committee on Water Data (1982) provides a generalized skew map for flood flows that is reproduced by Wurbs & James (2002) and McCuen (2005). Depending on the number of gage record years, regionalized skew coefficients are used either in lieu of, or in combination with, values computed from observed flows at the location of concern (Wurbs & Hoffpauir 2012).

The average annual damage or the expected value of annual damages, in dollars, at the downstream control point is a probability-weighted average of the full range of possible flood magnitudes. The decrease of flood storage capacity will lead to the increase of the flood prone area at downstream control points. The expected value of annual damage is determined by integrating the exceedance frequency ($P[x]$) versus damage function

$$E[X] = \int_{-\infty}^{\infty} x \frac{dP(x)}{dx} dx \tag{4}$$

RESULTS AND ANALYSIS

Six reservoirs, among nine reservoirs that have flood control storage (Table 1), are selected for reallocation to conservation storage, and three reservoirs, i.e., Whitney, Waco, and Proctor reservoirs, are simulated with the existing storage capacity. The reasons are that the Waco reservoir was recently reallocated by raising the designated top of the conservation pool elevation in October 2003. The Brazos River Authority operates the Proctor reservoir to meet water supply needs in the vicinity of the reservoir, and most conservation storage capacities in the Whitney reservoir are used for generating hydropower.

Tables 3 and 4 show the reliabilities results for three reallocation plans: individual, tributary reservoir storage reallocation, and all reservoir storage reallocation with natural and priority water rights. For natural water rights (Tables 3(a) and 4(a)), period reliability at the Waco reservoir is 9.61%, while volume reliability is 73.37% during the 1900–2007 simulation periods (39,559 days), because

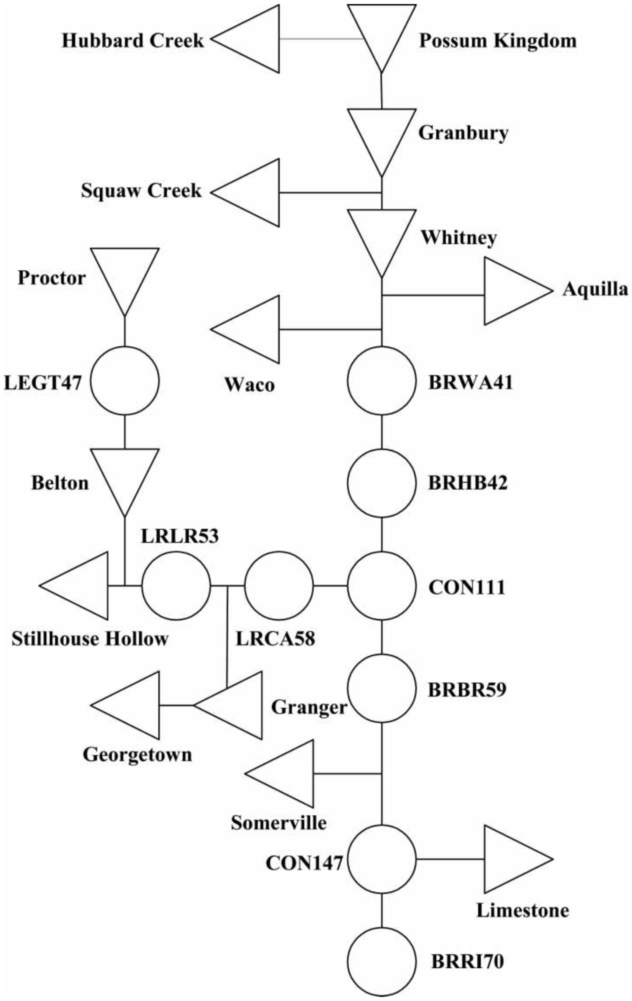

Figure 2 | Schematic layout of the multiple reservoir system.

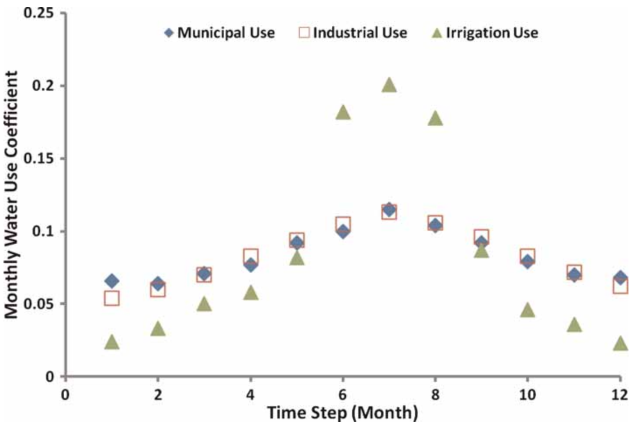

Figure 3 | Monthly water use distribution factors.

Table 2 | Maximum allowable discharges at five control points for flood control operations

Control point	Allowable discharge (10^6 m^3/yr)	Location
BRWA41	53,581	Brazos River at Waco
LEGT47	4,465	Leon River at Gatesville
LRCA58	8,930	Little River at Cameron
BRBR59	53,581	Brazos River at Bryan
BRRI70	53,581	Brazos River at Richmond

Source: Wurbs & Carriere (1988).

the small amount of shortage that occurred is spread out over the 1900–2007 simulation periods (Kim 2012). Also, reliabilities at the Waco reservoir are impacted by the Belton, Stillhouse Hollow, and Georgetown reservoir reallocations but not impacted by Aquilla, Granger, and Somerville reservoirs. For priority water rights, period (31.70%) and volume (32.80%) reliabilities for priority water rights at Hubbard Lake are significantly smaller than period (84.50%) and volume (86.37%) reliabilities, respectively, for natural water rights because the priority (2nd) of Possum Kingdom Lake is senior to the priority (3rd) of Hubbard Lake, and most of the stream flow in the river is constrained for conservation purpose use of Hubbard Lake, but is accessible to Possum Kingdom Lake. Proctor reservoir is impacted by systematic Belton and Stillhouse reservoir storage reallocation, but not impacted by individual Belton or Stillhouse reservoirs. Squaw Creek is not impacted by other reservoir storage reallocation with either kind of water rights. Also, both water rights show the increase of reliability by reservoir storage reallocation and provide reasonable water resources distribution in the reliabilities of most reservoirs, except that three reservoirs for natural water right option and two reservoirs for priority water rights option are below 90%.

Tables 5 and 6 provide the frequency analysis results, i.e., expected value, and statistics results, i.e., the mean and standard deviation of the 1900–2007 maximum annual reservoir storage, for six reservoirs under two kinds of water rights. The log-Pearson Type III distribution function is applied to maximum annual reservoir storage contents. Probability distribution functions, i.e., log-Pearson type III, are applicable to homogenous datasets representing the behavior of a particular phenomenon. The annual

Table 3 | Period reliability analysis for different reallocation reservoir plans

(a) Based on natural water rights			Individual reservoir (%)						Tributary reservoirs (%)				
Reservoir ID	**Total diversion (10^6 m^3/yr)**	**Original (%)**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hubbard	97	84.50	84.50	84.50	84.50	84.50	84.50	84.50	84.50	84.50	84.50	84.50	84.50
Possum	392	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Granbury	112	99.30	99.30	99.30	99.30	99.30	99.30	99.30	99.30	99.30	99.30	99.30	99.30
Sqwcrk	40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40
Whitney	27	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Aquila	24	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Lkwaco	138	9.61	9.61	9.70	9.65	9.62	9.61	9.61	9.70	9.62	9.70	9.70	9.70
Prctor	34	99.58	99.58	99.58	99.58	99.58	99.58	99.58	99.58	99.58	99.58	99.58	99.58
Belton	194	98.72	98.72	99.13	98.72	98.72	98.72	98.72	99.13	98.72	99.13	99.13	99.13
Stlhse	117	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Grgtwn	23	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Grnger	34	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Smrvle	83	98.32	98.32	98.32	98.32	98.32	98.32	99.16	98.32	98.32	98.32	98.32	99.16
Lmstne	112	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55

(b) Based on priority water rights			Individual reservoir (%)						Tributary reservoirs (%)				
Reservoir ID	**Total diversion (10^6 m^3/yr)**	**Original (%)**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hubbard	97	31.70	31.70	31.70	31.70	31.70	31.70	31.70	31.70	31.70	31.70	31.70	31.70
Possum	392	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Granbury	112	99.75	99.75	99.75	99.75	99.75	99.75	99.75	99.75	99.75	99.75	99.75	99.75
Sqwcrk	40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40	53.40
Whitney	27	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Aquila	24	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Lkwaco	138	96.59	96.59	96.59	96.59	96.59	96.59	96.59	96.59	96.59	96.59	96.59	96.59
Prctor	34	92.11	92.11	92.14	92.11	92.11	92.11	92.11	92.14	92.11	92.14	92.14	92.14
Belton	194	99.49	99.49	99.73	99.49	99.49	99.49	99.49	99.73	99.49	99.73	99.73	99.73
Stlhse	117	97.72	97.72	97.72	98.43	97.72	97.72	97.72	98.43	97.72	98.43	98.43	98.43
Grgtwn	23	97.84	97.84	97.84	97.84	98.22	97.84	97.84	97.84	98.22	98.22	98.22	98.22
Grnger	34	99.63	99.63	99.63	99.63	99.63	99.95	99.63	99.63	99.95	99.95	99.95	99.95
Smrvle	83	98.32	98.32	98.32	98.32	98.32	98.32	99.16	98.32	98.32	98.32	98.32	99.16
Lmstne	112	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55	98.55

A: Aquila, B: Belton, C: Stlhse, D: Grgtwn, E: Grnger, F: Smrvle.
Case 1: Belton and Stlhse.
Case 2: Grgtwn and Grnger.
Case 3: Belton, Stlhse, Grgtwn, and Grnger.
Case 4: Aquila, Belton, Stlhse, Grgtwn, and Grnger.
Case 5: Aquila, Belton, Stlhse, Grgtwn, Grnger, and Smrvle.

Table 4 | Volume reliability analysis for different reallocation reservoir plans

(a) Based on natural water rights

			Individual reservoir (%)						**Tributary reservoirs (%)**				
Reservoir ID	**Total diversion (10^6 m^3/yr)**	**Original (%)**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hubbard	97	86.37	86.37	86.37	86.37	86.37	86.37	86.37	86.37	86.37	86.37	86.37	86.37
Possum	392	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Granbury	112	99.25	99.25	99.25	99.25	99.25	99.25	99.25	99.25	99.25	99.25	99.25	99.25
Sqwcrk	40	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68
Whitney	27	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Aquila	24	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Lkwaco	138	72.37	72.40	72.40	72.38	72.38	72.37	72.37	72.40	72.38	72.40	72.43	72.43
Prctor	34	99.56	99.56	99.56	99.56	99.56	99.56	99.56	99.56	99.56	99.56	99.56	99.56
Belton	194	99.13	99.13	99.40	99.13	99.13	99.13	99.13	99.40	99.13	99.40	99.40	99.40
Stlhse	117	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Grgtwn	23	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Grnger	34	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Smrvle	83	98.71	98.71	98.71	98.71	98.71	98.71	99.19	98.71	98.71	98.71	98.71	99.19
Lmstne	112	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75
		94.95	94.95	94.99	94.95	94.95	94.95	94.97	94.99	94.95	94.99	94.99	95.02

(b) Based on priority water rights

			Individual reservoir (%)						**Tributary reservoirs (%)**				
Reservoir ID	**Total diversion (10^6 m^3/yr)**	**Original (%)**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hubbard	97	32.80	32.80	32.80	32.80	32.80	32.80	32.80	32.80	32.80	32.80	32.80	32.80
Possum	392	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Granbury	112	99.84	99.84	99.84	99.84	99.84	99.84	99.84	99.84	99.84	99.84	99.84	99.84
Sqwcrk	40	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68	60.68
Whitney	27	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Aquila	24	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Lkwaco	138	99.08	99.08	99.08	99.08	99.08	99.08	99.08	99.08	99.08	99.08	99.08	99.08
Proctor	34	93.29	93.29	93.35	93.29	93.29	93.29	93.29	93.35	93.29	93.35	93.35	93.35
Belton	194	99.67	99.67	99.83	99.67	99.67	99.67	99.67	99.83	99.67	99.83	99.83	99.83
Stlhse	117	98.02	98.02	98.02	98.64	98.02	98.02	98.02	98.64	98.02	98.64	98.64	98.64
Grgtwn	23	98.13	98.13	98.13	98.13	98.57	98.13	98.13	98.13	98.57	98.57	98.57	98.57
Grnger	34	99.76	99.76	99.76	99.76	99.76	99.97	99.76	99.76	99.97	99.97	99.97	99.97
Smrvle	83	98.71	98.71	98.71	98.71	98.71	98.71	99.19	98.71	98.71	98.71	98.71	99.19
Lmstne	112	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75	98.75
		93.62	93.62	93.64	93.67	93.63	93.63	93.65	93.70	93.63	93.71	93.71	93.74

Table 5 | Flood frequency for reservoir storage expected value for different reservoir reallocation plans based on log-Pearson type III distribution

(a) Based on natural water rights (10^7 m^3/yr)

		Individual reservoirs						Tributary reservoirs				
Reservoir ID	**Original**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Whitney	276.2	276.2	276.1	276.2	276.2	276.2	276.2	276.1	276.2	276.1	276.1	276.1
Aquila	21.1	21.2	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.2	21.2
Lkwaco	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Proctor	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Belton	76.5	76.5	81.4	76.2	76.5	76.5	76.5	81.3	76.5	81.2	81.2	81.2
Stlhse	122.4	122.4	122.4	122.9	122.4	122.4	122.4	122.9	122.4	122.9	122.9	122.9
Grgtwn	22.0	21.9	22.0	22.0	22.1	22.0	22.0	22.0	22.1	22.1	22.0	22.0
Grnger	21.8	21.7	21.8	21.8	21.8	24.8	21.8	21.8	24.7	24.7	24.7	24.7
Smrvle	19.9	19.9	19.9	19.9	19.9	19.9	24.6	19.9	19.9	19.9	19.9	24.6

(b) Based on priority water right (10^7 m^3/yr)

		Individual reservoir						Tributary reservoirs				
Reservoir ID	**Original**	**A**	**B**	**C**	**D**	**E**	**F**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Whitney	58.4	58.4	56.4	56.4	58.4	56.4	58.4	58.2	56.4	56.4	56.4	58.2
Aquila	7.7	9.3	7.5	7.5	7.7	7.5	7.7	7.7	7.5	7.5	9.0	9.3
Lkwaco	21.6	21.7	21.3	21.3	21.6	21.3	21.6	21.7	21.3	21.3	21.3	21.7
Proctor	10.5	10.5	10.2	10.2	10.5	10.2	10.5	10.5	10.2	10.2	10.2	10.5
Belton	62.5	62.5	67.8	62.5	62.5	62.4	62.5	67.8	62.4	67.7	67.7	67.7
Stlhse	31.2	31.2	31.1	35.9	31.2	31.0	31.2	36.2	31.0	35.9	35.9	36.2
Grgtwn	4.9	4.9	4.9	4.9	6.2	4.9	4.9	4.9	6.2	6.2	6.2	6.2
Grnger	11.2	11.2	11.2	11.2	11.2	13.9	11.2	11.2	13.9	13.9	13.9	13.9
Smrvle	19.4	19.4	19.4	19.4	19.4	19.4	24.1	19.4	19.4	19.4	19.4	24.2

series of naturalized flows represent homogenous, while those of regulated flows and reservoir storage are subject to non-homogenous because of the effects of reservoir operations. However, in this study, non-homogenous characteristics of reservoir storage are not critical because the purpose of this study is to evaluate the relative impact of the reservoir location on other reservoir operations. For natural water rights, expected values for Whitney, Waco, and Proctor reservoirs do not show a difference under several reallocation strategies. However, for priority water rights, the expected value of Whitney, Waco, and Proctor reservoirs, and the mean value of Whitney and Proctor reservoirs, decrease by 1×10^7 or 2×10^7 m^3, respectively, when any one or more reservoirs of Belton, Stillhouse Hollow, and Granger are reallocated. The reason for this is that the flood control storage volume is decreased by storing more streamflow by other reservoirs reallocated and located into the same tributary. For natural water rights, expected values for five reservoirs, except the Georgetown reservoir, increase when the flood control volume is reallocated to conservation purpose. This indicates that reallocation of the Georgetown reservoir does not make an impact on other reservoirs from the view of flood frequency analysis, as the mean and standard deviation in Table 6 provide the same results. However, for priority water rights, the patterns are different from natural water rights. Expected values, for each reservoir that has its reservoir storage volume reallocated, show increase patterns that are the same as the mean and standard deviation.

Table 6 | Statistical analysis of peak annual reservoir storage volume

(a) Based on natural water rights (10^7 m^3/yr)

	Original		**Individual reservoir (%)**												**Tributary reservoirs**									
			A		**B**		**C**		**D**		**E**		**F**		**Case 1**		**Case 2**		**Case 3**		**Case 4**		**Case 5**	
Reservoir ID	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Whitney	276.4	91.8	276.4	91.8	276.3	91.8	276.4	91.8	276.4	91.8	276.4	91.8	276.4	91.8	276.3	91.8	276.4	91.8	276.3	91.8	276.3	91.8	276.3	91.8
Aquila	21.7	9.4	21.8	9.3	21.7	9.4	21.7	9.4	21.7	9.4	21.7	9.4	21.7	9.4	21.7	9.4	21.7	9.4	21.7	9.4	21.8	9.3	21.8	9.3
Lkwaco	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6	5.2	1.6
Proctor	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2	6.9	1.2
Belton	79.2	41.6	79.2	41.6	84.9	41.6	79.0	41.5	79.2	41.6	79.2	41.6	79.2	41.6	84.8	41.5	79.2	41.6	84.7	41.5	84.7	41.5	84.7	41.5
Stlhse	128.6	32.2	128.6	32.2	128.6	32.3	129.1	31.8	128.6	32.2	128.6	32.2	128.6	32.2	129.1	31.8	128.6	32.2	129.1	31.8	129.1	31.8	129.1	31.8
Grgtwn	24.1	5.3	23.9	5.4	24.1	5.3	24.1	5.3	24.3	5.2	24.1	5.4	24.1	5.3	24.1	5.3	24.3	5.2	24.3	5.2	24.1	5.3	24.1	5.3
Grnger	21.7	13.5	21.6	13.4	21.7	13.5	21.7	13.5	21.7	13.5	24.8	13.7	21.7	13.5	21.7	13.5	24.8	13.7	24.8	13.7	24.8	13.7	24.8	13.7
Smrvle	21.2	9.7	21.2	9.7	21.2	9.7	21.2	9.7	21.2	9.7	21.2	9.7	27.0	10.1	21.2	9.7	21.2	9.7	21.2	9.7	21.2	9.7	27.0	10.1

(b) Based on priority water right (10^7 m^3/yr)

	Original		**Individual reservoir (%)**												**Tributary reservoirs**									
			A		**B**		**C**		**D**		**E**		**F**		**Case 1**		**Case 2**		**Case 3**		**Case 4**		**Case 5**	
Reservoir ID	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**S.**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Whitney	56.7	44.5	56.7	44.5	56.7	44.4	55.0	34.3	56.7	44.5	55.0	34.3	56.7	44.5	56.6	43.5	55.0	34.3	55.0	34.3	55.0	34.3	56.6	43.5
Aquila	7.7	3.8	9.3	3.8	7.7	3.8	7.6	3.3	7.7	3.8	7.6	3.3	7.7	3.8	7.7	3.8	7.6	3.3	7.6	3.3	9.1	3.2	9.3	3.8
Lkwaco	21.1	17.4	21.1	17.5	21.1	17.4	20.8	16.0	21.1	17.4	20.8	15.9	21.1	17.4	21.1	17.5	20.8	15.9	20.8	16.0	20.8	16.0	21.1	17.4
Proctor	10.5	12.9	10.5	12.9	10.5	12.9	10.2	11.6	10.5	12.9	10.2	11.6	10.5	12.9	10.5	12.9	10.2	11.6	10.2	11.6	10.2	11.6	10.5	12.9
Belton	65.1	30.8	65.1	30.8	70.9	31.1	65.1	30.9	65.1	30.8	65.0	30.7	65.1	30.8	70.9	31.1	65.0	30.7	70.8	31.1	70.8	31.1	70.8	31.1
Stlhse	32.5	18.2	32.5	18.2	32.5	18.2	37.8	17.3	32.5	18.2	32.3	17.2	32.5	18.2	38.1	18.7	32.3	17.2	37.8	17.3	37.8	17.3	38.1	18.6
Grgtwn	5.2	2.5	5.2	2.5	5.2	2.5	5.2	2.5	6.7	2.5	5.2	2.6	5.2	2.5	5.2	2.5	6.8	2.6	6.8	2.6	6.8	2.6	6.8	2.6
Grnger	11.2	6.3	11.2	6.3	11.2	6.3	11.2	6.3	11.2	6.4	14.2	6.4	11.2	6.3	11.2	6.3	14.2	6.4	14.2	6.4	14.2	6.4	14.2	6.4
Smrvle	20.7	9.0	20.7	9.0	20.7	9.0	20.7	9.0	20.7	9.0	20.7	9.0	26.5	9.3	20.7	9.0	20.7	9.0	20.7	9.0	20.7	9.0	26.6	9.4

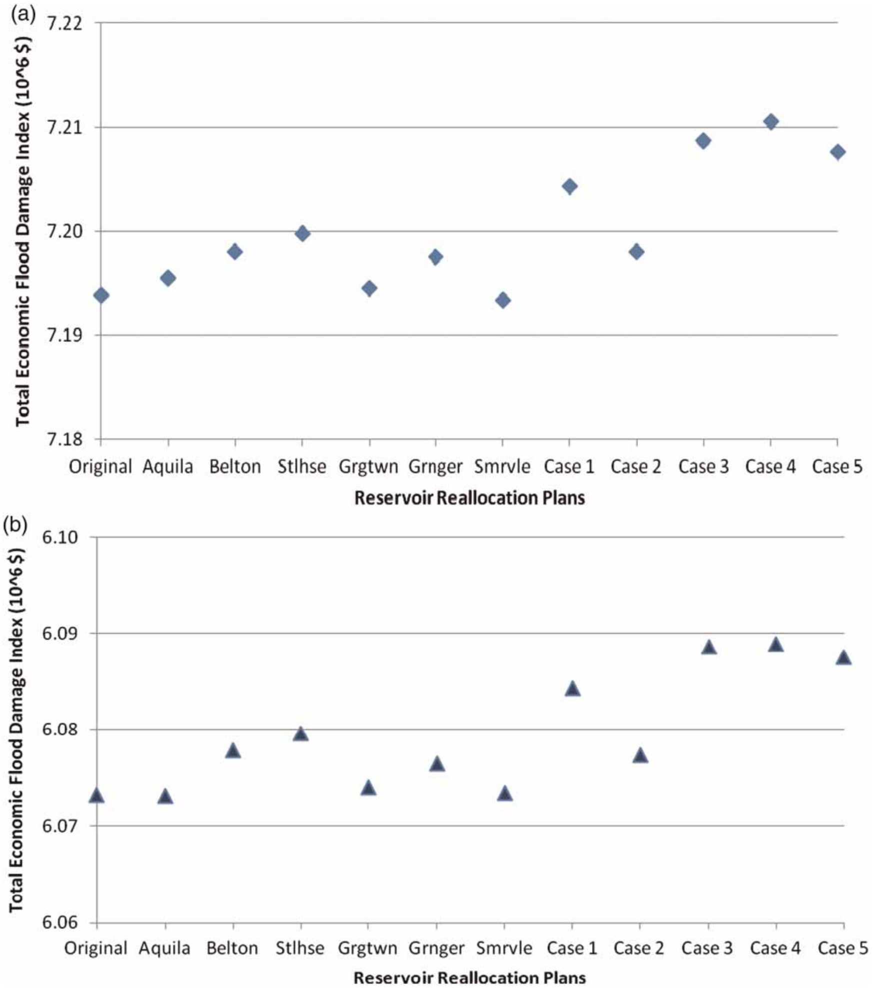

Figure 4 | Total economic flood damage index at four gage stations based on priority and natural water rights. (a) Natural water rights. (b) Priority water rights.

Figures 4(a) and 4(b) provide the changes in pattern of total economic flood damage index that are summed at four control points, including BRHB42, CON111, CON147, and BRRI70. The economic flood damage computed, based on log-Pearson type III, depends on the maximum values. The economic flood damage of natural water rights is 19% higher than that of priority water rights, although the mean value of natural water rights is lower than those of priority water rights because the maximum value of natural water rights is higher than that of priority water rights. In particular, as shown in Figure 4, the miniscule differences of economic flood damage for several plans show that the multiple reservoirs system is more effective in controlling the damages occurring at downstream control points.

SUMMARY AND CONCLUSION

The reliabilities and frequency analysis simulation results for three reallocation plans provide the criteria for selecting the reservoir location for reallocation and demonstrate the relative impact with natural and priority water rights for reservoir operating systems. Applications of the WAM/WRAP System by the Texas water management community to date have been limited to reservoir conservation pools, while ignoring flood control pools. This research included a comparison of flood control operation and application of expanded WRAP simulation features for modeling flood control operations, to the system of nine multiple-purpose Corps of Engineers reservoirs that contain flood control pools under two kinds of priority and natural water rights. Indices were developed for quantifying flood control capacities provided by the multiple reservoirs' system with several reservoir reallocation plans. The losses in flood control pools by reallocation result in increases in water supply reliability, frequency to flood control pool, and flood damage at downstream control points. Based on reliability, flood frequency, and economic flood damage, conclusions are drawn that show the impact of reservoir operation modifications on other reservoir systems is an inevitable phenomenon, and the determination of a reservoir should be determined from the alternative evaluation index of both conservation and flood control pools. Also, the WRAP/WAM-based simulation study, performed with the modified WAM dataset developed in this study, demonstrates the potential of the reservoir storage reallocation for conservation and flood control in multiple-purpose reservoir system operations.

REFERENCES

Babel, M. S., Das Gupta, A. & Nayak, D. K. 2005 A model for optimal allocation of water to competing demands. *Water Resour. Manage.* **19**, 693–712.

Booker, J. F. 1995 Hydrologic and economic-impacts of drought under alternative policy responses. *Water Resour. Bull.* **31**, 889–906.

Craney, P. W. 1996 Operation of water supply reservoirs for flood mitigation: hydrologic and institutional considerations. MS Thesis, Texas A&M University, College Station, Texas.

Ford, D. T. 1990 Reservoir storage reallocation analysis with PC. *J. Water Resour. Plan. Manage.* **116**, 402–416.

George, B. A., Malano, H. M., Tri, V. K. & Turral, H. 2004 Using modelling to improve operational performance in the Cu Chi irrigation system, Vietnam. *Irrig. Drain.* **53**, 237–249.

HDR Engineering INC. 2006 *Brazos G regional water plan (2006), regional water plan: volume 1: executive summary and regional water plan*. Austin, Texas.

Interagency Committee on Water Data 1982 *Guidelines for Determining Flood Flow Frequency*. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, US Geological Survey, Reston, Virginia.

Johnson, W. K., Wurbs, R. A. & Beegle, J. E. 1990 Opportunities for reservoir-storage reallocation. *J. Water Resour. Plan. Manage.* **116**, 550–566.

Kim, T. J. 2011 Application of water rights priority and natural priority concepts to river and reservoir operation systems. *Can. J. Civil Eng.* **38**, 650–660.

Kim, T. J. 2012 Evaluating the impacts of instream flow on water supply for municipal and irrigation use. *River Res. Appl.* **20**, 247–254.

Kim, T. J. & Wurbs, R. A. 2011a Development of a condensed model for managing of a particular river/reservoir system based on Texas Water Availability Model (WAM) Dataset. *KSCE J. Civil Eng.* **15**, 205–214.

Kim, T. J. & Wurbs, R. A. 2011b Development of monthly naturalized flow using Water Rights Analysis Package (WRAP)-based methods. *KSCE J. Civil Eng.* **15**, 1299–1307.

Kim, T. J. & Wurbs, R. A. 2011c Modeling river/reservoir system management with the expanded WRAP. *KSCE J. Civil Eng.* **15**, 1457–1467.

Labadie, J. W. 2004 Optimal operation of multireservoir systems: state-of-the-art review. *J. Water Resour. Plan. Manage.* **130**, 93–111.

Maddock, I. P., Bickerton, M. A., Spence, R. & Pickering, T. 2001 Reallocation of compensation releases to restore river flows and improve instream habitat availability in the upper Derwent catchment, Derbyshire, UK. *Regul. River.* **17**, 417–441.

McCuen, R. A. 2005 *Hydrologic Analysis and Design*. Prentice Hall, New Jersey, USA, 859 pp.

McMahon, G. F. & Farmer, M. C. 2004 Reallocation of federal multipurpose reservoirs: principles, policy, and practice. *J. Water Resour. Plan. Manage.* **130**, 187–197.

Rani, D. & Moreira, M. M. 2010 Simulation-optimization modeling: a survey and potential application in reservoir systems operation. *Water Resour. Manage.* **24**, 1107–1138.

Simonovic, S. P. & Qomariyah, S. 1993 Reassessment management strategies for Wonogiri reservoir in central Java. *Water Int.* **18**, 207–216.

Texas Commission on Environmental Quality 2012 Available at: http://www.tceq.texas.gov/permitting/water_supply/water_rights/wam.html (accessed 5 February 2012).

Texas Water Development Board 2006 *Reallocation of Storage in Federal Reservoirs for Future Water Supply*. EC Project/Proposal No. 4027, Espey Consultants, Inc., Austin, Texas.

Wood, A. W., Lettenmaier, D. P. & Palmer, R. N. 1997 Assessing climate change implications for water resources planning. *Clim. Change* **37**, 203–228.

Wurbs, R. A. 2005a Comparative evaluation of generalized river/reservoir system models. Technical Report-255, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. 2005b Texas Water Availability Modeling System. *J. Water Resour. Plan. Manage.* **131** (4), 270–279.

Wurbs, R. A. 2012a Water rights analysis package (WRAP) modeling system reference manual. Technical Report-255, 6th edn, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. 2012b Water rights analysis package (WRAP) modeling system users manual. Technical Report-256, 6th edn, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. & Cabezas-Canelos, L. M. 1987 Analysis of reservoir storage reallocation. *J. Hydrol.* **92**, 77–95.

Wurbs, R. A. & Carriere, P. E. 1988 Evaluation of storage reallocation and related strategies for optimizing reservoir system operations. Technical Report-145, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. & Carriere, P. E. 1993 Hydrologic simulation of reservoir storage reallocations. *Int. J. Water Resour. D.* **9**, 51–64.

Wurbs, R. A. & James, W. P. 2002 *Water Resources Engineering*. Prentice Hall, New Jersey.

Wurbs, R. A. & Kim, T. J. 2008 Extending and condensing the Brazos river basin water availability model. Technical Report-340, Texas Water Resources Institute, College Station, Texas.

Wurbs, R. A. & Kim, T. J. 2011 River flows for alternative conditions of water resources development. *J. Hydrol. Eng.* **16** (2), 148–156.

Wurbs, R. A. & Hoffpauir, R. J. 2012 Water Rights Analysis Package (WRAP) Daily Modeling System. Technical Report-430. Texas Water Resource Institute, College Station, TX.

First received 20 March 2013; accepted in revised form 26 September 2013. Available online 21 November 2013