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Dear Sir:

We are submitting the re-revised version of the manuscript “Integrated Water Management for Environmental Flows in the Rio Grande,” by Samuel Sandoval-Solis and Daene C. McKinney for possible publication in the Journal of Water Resources Planning and Management. The review comments have been taken into consideration in the revision and a response to the reviewers is included as well.

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Sincerely,

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Integrated Water Management for Environmental Flows in the Rio Grande

S. Sandoval-Solis\textsuperscript{1} A.M.ASCE and D. C. McKinney\textsuperscript{2}, M.ASCE

Abstract:
In the Rio Grande transboundary basin, environmental flows have not been considered as an integral part of the water management. This research focuses in the Big Bend, a reach located along the Rio Grande mainstem. Important natural regions of the Chihuahuan Desert are threatened due to the lack of environmental flows. In this paper is estimated the maximum volume of water available for environmental flows without affecting human and international water requirements, and without increasing the flood risk in Presidio-Ojinaga. Environmental flows are proposed based on an analysis of the prior reservoir alteration hydrology of the river. A planning model was built to simulate the water allocation system and evaluate alternative policies. A reservoir re-operation policy for Luis L. Leon reservoir is proposed to supply environmental flows without violating the system constraints. The policy that supplies the maximum water to the environment is two thirds (66\%) of the prior reservoir alteration conditions; it also improves human water supply, treaty obligations and decreases flood risk.

Keywords: Environmental Flows, Reservoir Re-Operation, Integrated Water Management, Adaptive Management, Rio Grande

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Introduction

Water management that attempts to balance competing uses is a common factor in many modern water resource systems. Sustainable water systems are those designed to meet present and future water demands, while maintaining a range of hydrologic variation necessary to preserve the ecological and environmental integrity of the basin (Loucks 1997). The previous definition contains several uncertainties. What is the current and future water availability? This estimation is undetermined given the alteration of nature by humans, land use change, greenhouse gas emissions and climate change. What are society’s water needs now and in the future? It is challenging to define current water needs and anticipate the values that future generations will impose on water and natural resources. What is the environmental integrity of the basin? It is difficult to determine the future water requirements and land use practices to preserve the environment. This paper presents an integrated water management approach to meet current and future water needs, while rehabilitating some elements of the native ecosystem, considering the historic hydrology of a specific basin: the Rio Grande.

Achieving sustainability in transboundary basins is challenging due to the existence of international agreements. This is the case of the Rio Grande/Bravo Basin (RGB Basin), a transboundary basin shared by the United States (U.S.) and Mexico (Figure 1.a). Environmental flows have not been considered as part of the water management in the RGB basin. This paper focuses on the Big Bend reach (BB reach), a region situated along the Rio Conchos mainstem from Luis L. Leon reservoir to its confluence with the RGB and along the RGB mainstem from the cities of Presidio-Ojinaga to Amistad reservoir (Figure 1.b). Important pristine areas such as the Big Bend National and State Park in the U.S., the Maderas del Carmen, Cañon de Santa Elena and Ocampo Natural Reserve Areas in Mexico are threatened due to the lack of water
management for environmental purposes. In 2010, a joint statement by the presidents Barak Obama (U.S.) and Felipe Calderon Hinojosa (Mexico) recognized the fragility and uniqueness of this region, they instruct their staff to initiate a process to recognize and designate Big Bend as a natural area of binational interest (Obama and Calderon 2010).

Since 2008, an independent group of scientists and individuals, from both countries, has explored several strategies to improve the environmental conditions in the BB reach, including the feasibility of providing environmental flows (e-flows) because of its unique characteristics: (a) there is water flowing in the reach but the flow regime is not optimal for environmental purposes, (b) infrastructure already exists to deliver e-flows from Luis L. Leon (LLL) reservoir on the Rio Conchos in Mexico, and (c) water for e-flows is not a consumptive use (except for the conveyance losses), water releases from LLL reservoir are captured below BB reach in Amistad reservoir. The main problems associated with an environmental policy are: (a) about 80% of the water in this region comes from Mexico namely the Rio Conchos, equity issues arise because in order to provide environmental benefits to both countries most of the water comes from Mexico, (b) there is a high flood risk at Presidio-Ojinaga valley (P-O Valley), any environmental policy must consider the flood risk in this area and (c) any e-flows policy must follow the water division between the U.S. and Mexico stated in the Treaty of 1944 (IBWC 1944).

How much water does the environment need? How much water is available for environmental purposes? Where could this water come from? This research proposes a set of e-flows based on a streamflow analysis of the basin. Then, a water management policy is proposed to supply e-flows that considers all the water sources, system constraints, and local and international water allocation rules. The objective of this research is to estimate the maximum volume of water available for e-flows in the BB reach, the maximum physically feasible
solution. This values will be useful during negotiations for determining strategies to include the environment as an integral part of the water management of the basin. The authors prove that it is possible to manage the system to provide e-flows without increasing flood risk in the P-O valley, and without affecting human water supply and the international treaty obligations.

**Literature Review**

Before the 1990’s, water management for environmental purposes was limited to water quality standards and minimum flow requirements. In the last two decades, this has changed towards managing rivers to achieve a more natural flow regime, capturing the seasonal and inter-annual flow variability, as well as the magnitude, timing and frequency of different flow conditions (Postel and Richter 2003). Methodologies to determine e-flows can be divided into four types: (1) statistical methods, such as the Tenant or Indicators of Hydrologic Alteration (IHA) methods, these methods analyze the historical hydrology to identify natural flow conditions and prescribe flow recommendations (Tennant 1975, Richter et al. 1996), (2) hydro-geomorphic methods, such as the Near-Census River Assessment and Rehabilitation method, which relates the hydrodynamics of the river with its morphology to design adequate habitat for the environment (Pasternack 2011), (3) instream habitat methods, such as the Instream Flow Incremental method, which relates different flows with habitat changes using predetermined preferences for specific fish species (Bovee 1978) and (4) holistic methods, such as the Building Block method (Tharme and King 1998) or the Benchmark Method (Brizga et al. 2002), these methods use multidisciplinary experts to define a flow regime intended to achieve a particular objective or to determine acceptable degrees of departure from the natural flow regime.

The IHA method is used in this research to propose e-flows because data is available for a period with more desired hydrologic characteristics (IBWC 2011) and it is recommended for
planning level analyses (Tharme 2003). In the BB reach, several studies have analyzed the
environmental conditions. Moring (2002) analyzed the stream habitat, fish community and
macroinvertebrates. Schmidt et al. (2003), Dean and Schmidt (2011) and Dean et al. (2011)
analyzed the 20th century hydrology, the relation between flows, floods, sediment transport,
vegetation, and how these factors affected the evolution of the channel and flood plain.
Sandoval-Solis et al. (2010) estimated the hydrology prior to and after reservoir alteration.
Everitt (1998) described the spread of the invasive species of salt cedar (Tamarix spp.). The
WWF (2008) summarized the previous studies in a vision and fact sheet, these studies coincide
with the e-flows proposed here.

Models are built to evaluate water management policies, they are a representation of
water resource systems. Models for the RGB Basin include: planning models to address drought
strategies (Vigerstol 2002), conflict resolution (Tate 2002), water availability (RJBC 2004), and
water management scenarios (Sandoval-Solis 2011). Dean and Schmidt (2010) built a one
dimension streamflow discharge model to evaluate the effects of increased vegetation roughness
on declining channel capacity in the BB reach. While in some of these models environmental
water management is contemplated for other regions of the RGB Basin (Sandoval-Solis 2011),
none of them considered the BB reach. The model built in this research is based on the RGB
Basin model (Sandoval-Solis 2011) with two main differences: it is a tailor made model for the
necessities of the BB reach and is the most updated model. It is the only model that includes the

This research proposes a reoperation policy for LLL reservoir to provide more desired
flows in the RGB Basin mainstem, while meeting human and treaty water requirements, and
without increasing the flood risk at P-O Valley. Reservoir reoperation policies have been
proposed to improve the environment in large (Yang et al. 2007) and small basins (Thompson et al. 2011), transboundary basins (WB 2004), in multi-purpose systems (Bednarek and Hart 2005), considering renewable water sources (Yang et al. 2008), climate change (Thompson et al. 2011), temperature of released water (Olden and Naiman 2010) and to improve the dissolved oxygen in the system (Bednarek and Hart 2005). The main difference with these approaches is the development of an iterative process, e-flows and reservoir reoperation policies are modified interactively to determine the maximum volume of water available for the environment. The method proposed here estimates the physically and legally available volume of water available for the environment given the system constraints.

**Rio Grande Basin (RGB Basin)**

The RGB is a transboundary basin shared by the U.S. and Mexico (Figure 1.a); it has a drainage basin of 557,722 km$^2$ with an estimated population in 2010 of 10.5 million people (Patiño-Gomez et al. 2007). Important pristine areas in both countries depend on the water in the river for their environmental requirements. The Treaty of 1944 established the water allocation in this region; unfortunately, the environment was not considered in this agreement. As a result, the environment has deteriorated, signs of this deterioration are: the progressive channel narrowing (Dean and Schmidt 2010), flow alteration due to reservoir operation (Sandoval-Solis et al. 2010, Dean and Schmidt 2011 and Dean et al. 2011), the invasion of non-native species, e.g. salt cedar (*Tamarisk spp.* ) and giant cane (*Arundo donax*) (Everitt 1998), change from freshwater to estuarine ecosystem (Schmandt 2002) and the almost complete extinction of endemic riverine species, e.g. Rio Grande silvery minnow (*Hybognathus amarus*) (Bestgen and Platania 1991).

In November 2008, a group of scientists, NGOs and governmental institutions gathered in a workshop to discuss the environmental problems in the BB reach, their possible solutions, gaps
in knowledge and the required research to address them. There were two main outcomes of this workshop: (1) a declaration of a vision for the BB reach (WWF 2008), which states the required characteristics of the river to preserve, enhance and restore the riverine ecosystem for the benefit of humans and nature and (2) an independent scientific committee was created to address gaps in knowledge and design integral solutions based on science and understanding. This paper is part of the discussions and efforts to address integral and scientific solutions for improving the environment in the BB region.

Analysis of River Flow Conditions

The vision for the BB reach (WWF 2008) outlines its importance, dependence and connection with water sources in Mexico, and the qualitative characteristics to support a healthy riverine ecosystem. Some of the desired characteristics are: “A wandering, laterally unstable river channel; a river cross-section form that is relatively wide and shallow; a river with flows that maintain channel capacity” (WWF 2008). Dean and Schmidt (2011) identified these characteristics during their research regarding narrowing of the channel over the last century and the processes responsible for it. They found that prior to 1946 the channel at the BB reach was in dynamic disequilibrium, wherein the channel was widened during large flood events and subsequently narrowed during the intervening periods at a slower rate than today. Large flood events moved sediments and prevented any substantial accumulation. Since early 1900’s small reservoirs were constructed in the RGB Basin. In 1916 the completion of two large reservoirs altered the hydrology of the basin: La Boquilla in the Rio Conchos (in Chihuahua, Mexico) and Elephant Butte in the upper RGB (in New Mexico). Large mean annual flows happened prior 1920 with a steady decline since 1936 to 1946 (Dean and Schmidt 2011). In the 1940’s, the construction of Caballo reservoir in the RGB (1938) (in New Mexico) and Francisco I. Madero
reservoir in the San Pedro river (1949) (in Chihuahua, Mexico) modified the flow conditions in
the BB reach, storing the remaining flood water left in the upper RGB and Rio Conchos sub-
basin (Sandoval-Solis 2011). As a result, flow conditions changed after 1946, this was evident in
the higher rate of channel narrowing; nowadays, the RGB is a narrower river in the BB reach
(Dean and Schmidt 2011). This research considers pre-1946 conditions (large floods and lower
channel narrowing rate) as a benchmark of a healthier environment compared to recent
hydrologic conditions (less frequent large floods and higher channel narrowing rates).

Benchmarks

Flow conditions were estimated through a probabilistic streamflow analysis at Johnson
Ranch gage station using the IHA method (Sandoval-Solis et al. 2010). Mean daily discharge
data was obtained from the International Boundary and Water Commission (IBWC 2011).
Johnson Ranch streamflow records were extended until 1901 using a linear regression from data
of RGB below Rio Conchos gage station. Natural cycles of dry (1945-1985, 1993-2007) and wet
(1936-1944, 1986-1992) periods have been documented for the BB reach (Dean and Schmidt
2011). Two periods were analyzed: the prior to reservoir alteration period, Pre-1946, a 30 year
period (Jan. 1901 to Dec. 1913 and Jan. 1930 to Dec. 1946) and the post reservoir alteration
period, Post-1946, with data for 30 years (Jan. 1980 to Dec. 2009). For the post-1946 period, the
last thirty-year period (1980-2009) is selected to analyze the characteristics of the most recent
hydrology; it contains a whole hydrologic cycle: the wet period of the 1980’s (1984-1993), and
the severe and extended drought of the 1990’s (1994-2007).

Three flow categories are used as benchmarks to determine the flow characteristics in this
reach (Postel and Ritcher 2003): (i) Base Flows: median value of the mean daily flows for each
month, aimed to provide adequate habitat, maintain suitable water temperatures and dissolve
oxygen; (ii) **High Flows**: streamflows with a peak between the 75th (56 m³/s) and 95th (224 m³/s) percentile of the mean daily flows for the pre-1946 period, aimed to prevent riparian vegetation from encroaching into the channel and restore water quality conditions; and (iii) **Floods**: streamflows with a peak above the 95th percentile (224 m³/s) of the pre-1946 period. This last benchmark is subdivided into two types: (a) **Small floods** between the 95th percentile (224 m³/s) and below 1,100 m³/s, which is a threshold to account for the flood capacity of levees at P-O valley whose maximum flow capacity is 1,190 m³/s (IBWC 1971) and (b) **Large floods**, with a peak above 1,100 m³/s, these large floods may threaten the safety of the levees and are aimed to shape the physical character of river channel and provide longitudinal connectivity of the river.

Thresholds have been determined using the pre-1946 period to estimate the flow characteristics of a period with more frequent large floods and slow channel narrowing rates, and compare them with the post alteration period (post-1946). Other hydrologic analyses in the BB reach (Dean and Schmidt 2011, Dean et al. 2011) used mean annual flow, average flood and duration as benchmarks for flow conditions for pre-1944 (1936-1944) and post-1944 periods (1945-1985, 1986-1992, 1993-2008).

**Prior reservoir alteration conditions**

Figure 2 shows the median annual hydrograph for the pre-1946 period, its volume is 1,488 million m³ [Base flows: 1128, High flows: 48, Small floods: 312; units: million m³], base flows, high flows and small floods were derived from median daily values. Base flows varied from 11 m³/s in April to 98 m³/s in September. High flows occurred every year (T=1) in July, August, October and December; and every two to three years (2<T<3) in May, June and November. Two small floods occurred every year, one in September (peak flow = 407 m³/s) and another that usually happened in either, July (peak flow = 405 m³/s), August (peak flow = 396
m³/s) or October (peak flow = 422 m³/s). Figure 2 shows the case of the small flood in July. The combination of two small floods may have contributed to maintaining the RGB as a wide sandy multi-threaded river (Dean and Schmidt 2011, Dean et al. 2011). Sandoval-Solis et al. (2010) explain the methods of calculation and flow conditions for these and other return periods. The pre-1946 hydrograph (Figure 2) is used as a template for all the hydrographs evaluated here, the peak and duration of small floods and high flows are preserved, the base flow is the benchmark scaled to increase or decrease the environmental hydrograph.

Recent flow conditions

Figure 3 shows the median annual hydrograph for the post-1946 period, its volume is 571 million m³ [Base flows: 450, High flows: 52, Small floods: 69; units: million m³]. Base flows vary from 8 m³/s in April to 24 m³/s in September, these values represent half of their respective pre-1946 value for most of the months. High flows occurred every year (T=1) in May, June, July and August; and every two to three years (2<T<3) in March, April and October. Post-1946’s high flows occurred earlier in time (May-August), smaller in magnitude and more frequently than pre-1946 conditions; this pattern can be attributed to releases from LLL reservoir to be prepared for the monsoon season (June-October). Only one small flood occurred every two to three years in September (peak flow = 342 m³/s), which is less frequent and smaller than the pre-1946 flows. The reduction in frequency and magnitude of small floods may have contributed to the progressive channel narrowing of the BB reach.

Water Management in the Big Bend

All the water that reaches the RGB from tributaries and the gains along the mainstem are allocated to each country according to the 1944 Treaty (IBWC 1944). Each country distributes their treaty allotment and the water in their tributaries according to the regulations of each
country. In Texas, water is allocated according to the prior appropriation law (TCEQ 2006), and in Mexico water is allocated according to its water use (CONAGUA 2008a).

*Treaty of 1944*

The 1944 Treaty specifies the water allocation for the RGB Basin. In the BB reach, the U.S. receives an allocation of: (1) all the waters reaching the RGB from Pecos and Devil Rivers; Alamito and Terlingua Creeks, and Goodenough spring, (2) one third of the flow reaching the RGB from Rio Conchos, (3) one half of the gains along the RGB mainstem and (4) one half of the water at Fort Quitman from the RGB. In the BB reach, Mexico has the allocation of: (1) two thirds of the flow reaching the RGB from Rio Conchos, (2) one half of the gains along the RGB mainstem and (3) one half of the water at Fort Quitman from the RGB (IBWC 1944). Amistad international reservoir was built to store and manage the water for both countries in the upper RBG Basin, each country has its own storage account. The IBWC is the institution in charge of the execution and compliance of the 1944 Treaty.

*United States Water Management*

In Texas, the BB reach is denominated as the upper Rio Grande Basin (from Fort Quitman to Amistad), water is allocated using the prior appropriation rule: “first in time, first in right”; senior water rights are honored before junior water rights. During drought periods, the Texas Rio Grande Watermaster program administered by the Texas Commission on Environmental Quality (TCEQ) may impose reductions in water diversions, allocating water first to municipal and domestic use (TCEQ 2006).

*Mexican Water Management*

In Mexico, the National Water Commission (Comisión Nacional del Agua, CONAGUA) is the federal authority responsible for water management. CONAGUA executes the water
management in the tributaries and along the RGB mainstem in Mexico. Water demands are characterized by use; the National Water Law establishes the priority for all water uses (CONAGUA 2008a). Domestic and municipal users have the highest priority and two times their annual water demand must be stored in the reservoirs. Agricultural users are not guaranteed and their allocation depends on the available storage in the respective dam that supplies them. Each October, CONAGUA determines the available reservoir storage after deducting municipal allocations, evaporation and operation losses. Then, a negotiation between CONAGUA and the irrigation districts sets the agricultural water allocation for the coming water year. On the BB reach, LLL is managed for two purposes: water supply using the rule described above and for flood control operated at the discretion of CONAGUA. Water released for flood control is important because it reaches the confluence of the RGB and is accounted for treaty obligations.

**Water Planning Model for the Big Bend Reach**

The allocation of water in the Big Bend Reach is simulated using the Water Evaluation and Planning System (WEAP) platform (Yates et al. 2005). The water distribution algorithm mimics the allocation of water in the U.S., Mexico and the division of water established in the Treaty of 1944. The hydrologic record considered for this reach is 55 years (Oct. 1955-Sep. 2009). The *Big Bend model* is a water planning model that calculates the balance between inflows, change of storage in reservoirs, water demands and outflows. CONAGUA, TCEQ and IBWC provided data for inflows, streamflow data, capacities, storage-elevation curves and evaporation losses in reservoirs (Patiño-Gomez et al. 2007, CONAGUA 2008b, IBWC 2011). Table 1 shows the water demands considered in the model. The performance of the model was evaluated using a 40-year period of analysis (Oct. 1969-Sep. 2009) because during this period, Amistad and Luis L. Leon reservoirs were in operation and there are accurate records of water
diversions and reservoirs storage (CONAGUA 2008b). The index of agreement (IA) and coefficient of efficiency (CE) were estimated (Legates and McCabe 1999) for the two reservoirs: LLL (IA=0.998, CE=0.992) and Amistad (IA=0.993, CE=0.970). These indices were estimated in two gage stations: Rio Conchos at Ojinaga (IA=0.994, CE=0.976) and RGB at Johnson Ranch (IA=0.9998, CE=0.991), which is the location where the e-flows were determined. These indices show that the model performs very well (Moriasi et al. 2007) compared to the historic records, in all cases the values are larger than 0.95. The simulation process considers the repetition of the 55-year hydrologic record using the recent infrastructure. Monthly use coefficients are used to account for the seasonal variability for each demand (RJBC 2004).

**Environmental Water Management**

Water in the BB region is subject to competing water uses. Water is managed for human consumption, irrigation, meeting international agreements, water demands of downstream users (in Texas, Coahuila and Tamaulipas) and flood protection. However, the arrangement and size of the infrastructure provides an opportunity to release water from LLL reservoir in an environmental friendly pattern and capture it in Amistad reservoir without affecting the objectives mentioned above; i.e. “changing the timing, preserving the long term volume”.

The objective of this research is to estimate the maximum volume of water available for the environment. The authors hypothesized that it is possible to manage the system to provide base and high flows, and small floods without affecting the uses named above. The desired water management policy provides e-flows while meeting the following constraints: (1) human water uses below LLL reservoir are unaffected, (2) releases for environmental purposes should not exceed the levee capacity at P-O Valley [1,190 m³/s, (IBWC 1971)], (3) flood risk during the monsoon season at P-O valley is not increased and (4) the allocation of water under the 1944
Treaty is respected. The last constraint means the water that reaches the RGB from the Rio Conchos is divided according to the treaty and it is on average the same volume that this river has contributed historically to the treaty obligations[1954-2009, (IBWC 2011)] and that was projected when the treaty was signed (Orive-Alba 1945), between 50% to 60% of the treaty obligations.

If the authors’ hypothesis is true, this analysis can provide guidance during discussions regarding water available for the environment, because it quantifies the maximum amount of water that can be transferred from LLL to Amistad reservoir without affecting human water supply, flood risk at P-O valley or the treaty obligations.

Reservoir Reoperation Policy

The operation policy proposed for LLL reservoir considers water supply for the environment while meeting the constraints listed in the previous section. These are the considerations for the proposed policy: (1) LLL provides part of the base flows and the entirety of small floods to the BB reach, high flows are provided naturally from the rest of the water sources, (2) releases for base flow from LLL takes into account the rest of the water sources (RGB above Ojinaga, Alamito, Terlingua, and gains in Rio Conchos and RGB mainstem), median monthly values for each water source have been estimated and subtracted from the prescribed base flow, (3) releases at LLL are higher in magnitude and duration to meet the e-flows at Johnson ranch, (4) human water demands are fixed for the simulation period and they represent the current water rights (Table 1), this assumption recognizes that there is a small municipal water demand (< 1% of the total water rights) and the agriculture water rights (~99% of the total water rights) are not expected to increase in the future (personal communication, D. Treviño, CONAGUA’s technical advisor, 2010) and (5) inflows to LLL are tracked during two
seasons for operational decisions, wet (Jun. to Oct.) and dry (Nov. to May). Drought conditions are considered to exist when inflows during the previous wet or dry season are smaller than 250 or 200 million m$^3$, respectively; or when the storage in LLL is below the drought pool threshold.

A probabilistic analysis of LLL inflows (1949-2009) was carried out to define the drought thresholds, they were determined by comparing the water demands below LLL and the expected inflows considering a 70% exceedance probability. At the beginning of the dry season (Nov. 1$^{st}$), given that the inflows in the previous wet season are smaller than 250 million m$^3$, there is a 70% chance that the inflows in the following dry season will be at least 133 million m$^3$. Similarly, at the beginning of the wet season (Jun. 1$^{st}$), given that the inflows in the previous dry season are smaller than 200 million m$^3$, there is a 70% chance that the inflows in the following wet season will be at least 67 million m$^3$. The sum of these inflows (200 million m$^3$) is bigger than the annual water demand for human use below LLL considering seepage and evaporation losses, which is 196 million m$^3$. The authors propose a risk of 30% (70% exceedance probability) for the LLL reoperation policy; however, this value may change depending on negotiations and authorities adversity to risk.

The storage in LLL is divided into different zones (see Figure 4): (a) Flood control zone, storage dedicated to manage floods, (b) Environmental flows zone, storage dedicated to supply base flows and small floods for the environment, this zone is further divided into Base flow and Small floods zones, (c) Transition zone, storage dedicated to anthropogenic water users, a buffer storage between the drought and environmental flows zone, (d) Drought zone, storage dedicated to supply water during drought periods to humans and the environment and (e) Dead storage zone, unusable storage. Releases from LLL consist of water for human use and the environment

$$Releases_{t}^{LLL} = Releases_{t}^{Human} + Releases_{t}^{Env} \quad [1]$$
Releases for human use ($Releases_{t}^{Human}$, $t = 1, \ldots, t = 12$) are secured every month. Releases for the environment consist of base flows ($Base_{t}$, $t = 1, \ldots, 12$) and small floods ($SF_{t}$, $t = 7, \ldots, 10$)

$$Releases_{t}^{Env} = Base_{t} + SF_{t}$$  \[2\]

Two types of base flows are proposed: normal and drought. Normal base flows ($Base_{t}^{Normal}$) are released when LLL storage at the beginning of each month ($S_{t-1}^{LLL}$) is above the base flow storage threshold ($S_{t-1}^{Base\ Flow}$). Drought flows ($Base_{t}^{Drought}$) are released when the storage at the beginning of the month ($S_{t-1}^{LLL}$) is below the drought storage threshold ($S_{t-1}^{Drought}$) or for the whole season when the inflows in the previous wet ($I_{season-1}^{Wet}$) or dry ($I_{season-1}^{Dry}$) seasons are less than 250 or 200 million m$^{3}$, respectively. No base flow is released when the storage at the beginning of the month is in the transition zone ($S_{t-1}^{Base\ Flow} > S_{t-1}^{LLL} > S_{t-1}^{Drought}$). Base flows ($Base_{t}$, $t=1,\ldots, 12$) are released from LLL according to the rule:

$$Base_{t} = \begin{cases} Base_{t}^{Normal} & \text{if } S_{t-1}^{LLL} > S_{t-1}^{Base\ Flow} \\ Base_{t}^{Drought} & \text{if } S_{t-1}^{Drought} > S_{t-1}^{LLL} > S_{t-1}^{Dead} \\ Base_{t}^{Drought} & \text{if } I_{season-1}^{Wet} < 250 \\ Base_{t}^{Drought} & \text{if } I_{season-1}^{Dry} < 200 \\ 0 & \text{if } S_{t-1}^{Base\ Flow} > S_{t-1}^{LLL} > S_{t-1}^{Drought} \end{cases} \quad \text{for } t = 1, \ldots, 12, 11,12,1,2,\ldots,6,7,\ldots,10$$  \[3\]

Small floods are released when the LLL storage at the beginning of the month ($S_{t-1}^{LLL}$) is above the small flood threshold ($S^{Flood}$). No small floods are released if the storage at the beginning of the month ($S_{t-1}^{LLL}$) is below the small flood threshold ($S^{Small\ Flood}$) or if the inflows in the previous dry season ($I_{season-1}^{Dry}$) are smaller than 200 million m$^{3}$. Small floods ($SF_{t}$, $t = 7, \ldots, 10$) are released from LLL during July to October according to the rule:
Simulation Process

An iterative simulation process was used to determine the maximum volume of water available for the environment. First, an environmental hydrograph is proposed, e.g. a hydrograph of 900 million m\(^3\)/year [Base flows: 524, High flows: 41, Small floods: 335; units: million m\(^3\)]. Second, a set of storage thresholds \(S^{Flood}_{t} \), \(S^{Small\ Flood}_{t} \), \(S^{Base\ Flow}_{t}\), \(S^{Drought}_{t}\) and a drought base flow \(Base^{Drought}_{t}\) are proposed and entered in the model. Third, the model is run and results are analyzed. If results meet the constraints specified for the system, as stated above, the model is considered a feasible solution, otherwise the results are discarded. Several annual environmental hydrographs (1300, 1250, ..., 650, 600 million m\(^3\)/year) were evaluated using the template of the pre-1946 conditions. The peak and duration high flows are preserved in each annual hydrograph as suggested by Postel and Richter (2003), the peak of small floods is reduced to 375 m\(^3\)/s according to the suggestion of Big Bend National Park hydrologist (personal communication, J. Bennett, Hydrologist, Big Bend National Park, 2011). Base flow is the benchmark used to increase or decrease the annual environmental hydrograph. The feasible solution that supplied the largest flow through the Big Bend reach is the policy that provides the maximum water for the environment.

Results

Maximum Hydrograph for the Environment

According to the analysis reported here, the maximum amount of water that can be supplied to the BB Reach at Johnson Ranch without affecting other water users or treaty obligations, or increasing the flood risk in Ojinaga/Presidio is 982 million m\(^3\)/year [Base flow:
624, High flows: 36, Small floods: 322; units: million m$^3$] (see Figure 5 and Table 2). Base flows vary from 9 m$^3$/s in April to 56 m$^3$/s in September following the same pattern as the pre-1946 base flow conditions. High flows occurred every year (T<1.5) in July, August and October; and every two years (T=2) in December. One small flood occurs every two years in either September or October (peak flow=374 m$^3$/s) and every three years in either, July or August (peak flow=355 m$^3$/s). The drought base flows released are 44 million m$^3$/year, these drought base flows have the same distribution as the normal base flows. These results represent an improvement from post-1946 conditions (Figure 3), base flows are larger and follow the same pattern as the pre-1946 conditions, high flows and small floods occur more frequently at the right time and water can be released in drought periods. The volume of the hydrograph shown in Figure 5 is similar to the historic average at Johnson Ranch, which is 1004 million m$^3$/year (1955-2009), this means the proposed policy preserves the long-term volume while adjusting the timing of the deliveries in an environmental pattern. Table 2 shows the set of storage thresholds that combined with the reservoir reoperation policy make possible the delivery of the hydrograph in Figure 5.

Water supply system performance for stakeholders is evaluated using the sustainability index (SI) for water resources management. The SI is a summary index that integrates results of several performance criteria using a geometric average, its scale varies from 0 to 1 with 1 being the most desirable. The performance criteria selected to evaluate stakeholders are: reliability (time and volume), vulnerability, resilience and maximum deficit. These criteria have been selected because they represent the desired characteristics for the stakeholders’ water supply: a reliable water supply in time and volume that recovers fast from deficits (high resilience), when deficit happen the average and worst case deficit should be small (low vulnerability and maximum deficit) (Sandoval-Solis et. al. 2011). The SI ($SI^i$) for the $i^{th}$ water user is:
\[ SI^i = \left[ Rel_{\text{time}}^i \times Rel_{\text{vol}}^i \times Resil^i \times (1 - Vuln^i) \times (1 - Max.\ Def^i) \right]^{1/5} \]  \[5\]

Table 1 shows the SI for all water users. Two scenarios are compared, the Historic scenario (Historic) and the reservoir reoperation scenario (Reoperation). The results show that all the water demands supplied from LLL reservoir (Ag. DR-090, Ag. Rio Conchos and Mun. Rio Conchos) have a SI of 100%, meaning that their water demands are fully supplied during the whole period [100% reliability (time and volume) and resilience; 0% vulnerability and maximum deficit]. Also, US Municipal Rio Grande is fully supplied because it has the highest priority, the remaining water users have a SI less than 100% but greater than 75%. These results contrast with the Historic scenario SI values which are lower than 43%. In summary, the reservoir re-operation policy does not affect the water supply of any stakeholder in the region, on the contrary, it improves the water supply compared with the Historic scenario.

The Rio Conchos is one of the six tributaries whose waters contribute to the delivery of treaty obligations from Mexico to the U.S.. When the Treaty of 1944 was signed, the average annual outflow from this river was considered 770 million m\(^3\)/year, 59% of the treaty obligations (Orive-Alba 1945). The historic average and median outflow for the Rio Conchos from 1955 to 2009 are 782 and 661 million m\(^3\)/year; these values represent 60% and 51% of the treaty obligations, respectively. Similarly, the average and median outflow for the Rio Conchos in the Reoperation scenario are 732 and 609 million m\(^3\)/year; these values represent the 56% and 47% of the treaty obligations, respectively. Because the average and median annual outflow have a similar value and distribution (Figure 6) with the historic and treaty’s signature values, these results show that the reservoir reoperation policy does not harm the delivery of treaty obligations from Mexico to the US. Thus, the Rio Conchos will continue to contribute about the same amount of water to the treaty obligations, but with improved environmental conditions and human water supply.
The safety of the O-P valley from floods is considered in the Reoperation scenario. Until 2009, fifteen major flood events occurred in this valley, as shown in Table 3 (IBWC 1971 and 2011). In 1971, the levee capacity at Ojinaga/Presidio was upgraded for a 25-year return period flood estimated to be 1,190 m$^3$/s (IBWC 1971); however, four floods occurred after the levees were upgraded. In all of the cases from 1971 to 2009, daily streamflow values were close to or larger than the levee capacity, monthly values for these events are larger than 550 million m$^3$ (Sep. 1978). This monthly value is used as a threshold to identify months that are likely to experience flood events. In the Historic scenario 10 months higher than 550 million m$^3$ occur representing a flood risk of 18.2% (5.5-year return period), while in the Reoperation scenario only 7 events occur representing a flood risk of 12.7% (8-year return period). These results show that the proposed policy reduces the frequency of months when floods are likely to occur.

The volume of water conveyed in each of the seven floods after 1955 has been analyzed and compared with the Historic scenario at Ojinaga. In five flood events (1958, 1966 1978, 1990 and 2008) the volume of water passed through O-P valley is smaller than in the historic values, 18% less volume on average. On the contrary, in 2 flood events, 1991 and 1968, results from the Reoperation scenario are about 20% larger than the historic events. These mixed results show that the Reoperation policy has the potential to reduce flood damages; however, a more refined time scale reservoir operation-flooding model is required to properly address this issue. The authors acknowledge that results regarding flood risk are a coarse estimation, the purpose this analysis is to highlight the potential opportunity to improve flood risk management through a reservoir reoperation policy, such as the one proposed.

*Tradeoffs among Flow Conditions*
Figure 7 shows the tradeoffs between base flows (left Y-axis) and small floods (right Y-axis, inverse) for a set of different feasible solutions. These two variables are inversely correlated, as the base flow increases, the frequency of small floods decreases (the return period increases, T=1/frequency). For instance, an annual base flow of 300 million m$^3$ allows the delivery of small floods every year (T=1.2) in September-October and every two years (T=2) in July-August. In contrast, an annual base flow of 624 million m$^3$, as the maximum hydrograph, allows delivery of small floods every two years (T=2) in September-October and every three years (T=3.2) in July-August.

Figure 7 shows the different combinations of environmental flows that can be managed and their consequences. Providing more frequent small floods may help to preserve the width of the river channel; however, it may compromise the subsistence of the aquatic ecosystem because of low base flows all year long. On the contrary, reoperating LLL for high base flows may provide benefits for the aquatic ecosystem, but channel narrowing may resume due to the low frequency in small floods. This figure shows that while there is a hydrograph that can provide the maximum amount of water for environmental purposes (darker column in Figure 7), there are several combinations that can provide a wide range of base flows and small floods. These combinations should be analyzed by scientists and decision makers to determine which combination(s) can support the aquatic ecosystem with water all year around (through base flows), while at the same time keeping the channel open (through frequent small floods). Detailed research on the aquatic ecosystem and the geomorphology dynamics of the river are necessary to determine the combination that would be most beneficial for the environment.

Conclusions
The authors’ hypothesis was confirmed through this research, it is possible to manage water in the BB Reach to provide e-flows without affecting municipal, agricultural or treaty obligations and without increasing the flood risk in the P-O valley: “changing the timing, preserving the long term volume”. The reservoir reoperation policy increases the overall water supply for human water users in the U.S. and Mexico. Moreover, this policy reduces the frequency of months where floods are likely to occur. Under the proposed policy the outflow distribution for the Rio Conchos is similar to the historic and treaty’s signature conditions, meaning that about the same amount of water in the same time will be delivered to meet the treaty obligations from Mexico to the US. Furthermore, water released from LLL reservoir are recaptured in Amistad reservoir, where it is stored and re-distributed without affecting water users downstream.

The maximum annual amount of water that can be managed and delivered for e-flows in the Big Bend Reach at Johnson Ranch is 982 million m³, which is 66% of the pre-reservoir alteration conditions (1,488 million m³) and 98% of the historic average (1,004 million m³). Base flows delivered are 624 million m³/year, which represent 55% of the pre-1946 conditions (1,129 million m³), these base flows mimic the pre-alteration conditions. High flows and small floods are likely to occur with the same magnitude and similar frequency as in the pre-1946 conditions. The main difference is in the frequency for September-October small floods, in the reservoir reoperation policy they will occur every two years while in the pre-1946 conditions they used to happen every year. Besides the maximum annual hydrograph, other feasible solutions were found with different combinations of base flows and frequencies of small floods. In fact, there is an inverse relationship between these two benchmarks, an increase in base flow volume represents a decrease in small floods frequency and vice versa. These feasible solutions will help to understand the expected frequency of small floods given a particular base flow in the river.
Limitations

First, results from the reservoir re-operation policy are obtained assuming a repetition of the historic hydrology in this region, the authors acknowledge the potential non-stationarity of the hydrology due to climate change. Second, the annual hydrographs presented in this paper are a simplification of daily processes, further refinement in time scale may be necessary. Third, pilot e-flows and monitoring are necessary to evaluate the impact of e-flows in sediment transport and riverine ecosystem. Fourth, it is necessary to evaluate sediment transportation; moving sediment from the BB reach to Amistad may reduce the conservation storage in this reservoir. Fifth, flood risk results are a coarse approximation of the overall performance, detailed flood analysis and modeling is required to properly address the flood risk in P-O valley, including the operation of reservoir upstream LLL. Sixth, water quality issues are necessary to address in the BB Reach, primary concerns include high bacteria levels, salinity and nutrients (Sandoval-Solis 2011). Suggestions for future research include water quality, hydrologic and flood modeling; climate change analysis, sediment transport, and estimation of gains and conveyance losses.

Acknowledgements

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Table 1. Performance Criteria and Sustainability Index for water users, Historic and Reoperation Scenarios

Table 2. Maximum Environmental Hydrograph and Storage Levels for the Policy Proposed

Table 3. Historic Flows in the Big Bend Reach
### Table 1. Performance Criteria and Sustainability Index for water users, Historic and Reoperation Scenarios

<table>
<thead>
<tr>
<th></th>
<th>Demand (million m$^3$)</th>
<th>Historic</th>
<th>Reoperation</th>
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<tr>
<td></td>
<td>Rel(V)</td>
<td>Rel(T)</td>
<td>Res</td>
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<td>Ag. DR 090</td>
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**Table 2. Maximum Environmental Hydrograph and Storage Levels for the Policy Proposed**

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<th>Value</th>
<th>Unit</th>
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<th>Jul</th>
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* MCM – million m³.
### Table 3. Historic Flows in the Big Bend Reach

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Peak Flow (m$^3$/s)</th>
<th>Year</th>
<th>Month</th>
<th>Peak Flow (m$^3$/s)</th>
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<td>N/A</td>
<td>1958$^{[a]}$</td>
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<td>Sep</td>
<td>4,587</td>
<td>1966$^{[a]}$</td>
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<td>527</td>
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<td>1991$^{[b]}$</td>
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Data sources: (a) IBWC 1971 and (b) IBWC 2011; N/A – Not Available
Figure 1
Click here to download Figure: Fig1.pdf
Streamflow ($m^3/s$)

- $2 < T < 3$
- $T = 1$

- $P(75) = 56 \ m^3/s$
- $P(95) = 224 \ m^3/s$

Figure 3
Figure 4
Click here to download Figure: Fig4.pdf

The diagram illustrates the storage capacity and zones of a water management system. The vertical axis represents storage in million m$^3$, ranging from 0 to 900 million m$^3$. The horizontal axis represents time, marked from January (J) to December (D), broken down into months.

- **Flood Control Zone**: This zone represents the maximum storage capacity, marked at 900 million m$^3$.
- **Environmental Flow Zone**: Located below the Flood Control Zone, this zone is marked at 600 million m$^3$.
- **Transition Zone**: Below the Environmental Flow Zone, this zone is marked at 300 million m$^3$.
- **Drought Zone**: Below the Transition Zone, this zone is marked at 100 million m$^3$.
- **Dead Storage**: The lowest zone, marked at 0 million m$^3$.

Each zone is shaded differently to distinguish its purpose:
- Flood Control Zone: Solid black
- Environmental Flow Zone: Dashed black
- Transition Zone: Dash-dotted black
- Drought Zone: Dotted black
- Dead Storage: Solid black

The diagram shows the temporal distribution of storage across these zones, with specific values indicated for each month.
Streamflow (m$^3$/s)

- $2 < T < 3$
- $T = 1$
- $T = 2$
- $T = 3$

$P(75) = 56$ m$^3$/s

$P(95) = 224$ m$^3$/s
Figure 7
Click here to download Figure: Fig7.pdf
**Figure 1.** Rio Grande Basin

**Figure 2.** Flow Conditions in the Big Bend reach at Johnson Ranch, Pre-1946

**Figure 3.** Flow Conditions in the Big Bend reach at Johnson Ranch, Post-1946

**Figure 4.** Storage zones and thresholds for Luis L. Leon reservoir. Zone 0: Baseₜ=0; Zone 1: Baseₜ=Baseₜ^{\text{Drought}}, Zone 2: Baseₜ=Baseₜ^{\text{Normal}}, SFₜ=0. Zone 3: Baseₜ=Baseₜ^{\text{Normal}}, SFₜ=Releaseₜ^{\text{Flood}}. Baseₜ=Baseₜ^{\text{Drought}} at all times if \( I_{\text{wet}}^{\text{Season}} - 1 < 250 \) or \( I_{\text{dry}}^{\text{Season}} - 1 < 250 \). SFₜ=0 at all times if \( I_{\text{wet}}^{\text{Season}} - 1 < 250 \) or \( I_{\text{wet}}^{\text{Season}} - 1 < 250 \), units: million m$^3$. Wet Season: Jun. to Oct.; Dry season: Nov. to May.

**Figure 5.** Hydrograph that supplies the maximum amount water through the Big Bend reach

**Figure 6.** Annual outflow distribution of Rio Conchos at Ojinaga

**Figure 7.** Tradeoffs between base flows and return periods for small floods. Vertical bars are values of base flow, solid dots are July-August flood flows, and open dots are Sep-Oct flood flows.
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Manuscript Authors: Samuel Sandoval-Solis, Darlene C. McKinney

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Note: The worksheet is designed to automatically calculate the total number of printed pages when published in ASCE two-column format.

<table>
<thead>
<tr>
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<tr>
<td>Author Full Name:</td>
<td>Samuel Sandoval-Solis</td>
<td>Author Email: <a href="mailto:samsandoval@ucdavis.edu">samsandoval@ucdavis.edu</a></td>
</tr>
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</table>

The maximum length of a technical paper is 10,000 words and word-equivalents or 8 printed pages. A technical note should not exceed 3,500 word-equivalents in length or 4 printed pages. Approximate the length by using the form below to calculate the total number of words in the text it to the total number of word-equivalents of the figures and tables to obtain a grand total of words for the paper/note to fit ASCE format. Overlength papers must be approved by the editor; however, valuable overlength contributions are not intended to be discouraged by this procedure.

1. **Estimating Length of Text**

A. Fill in the four numbers (highlighted in green) in the column to the right to obtain the total length of text.

**NOTE: Equations take up a lot of space.** Most computer programs don’t count the amount of space around display equations. Plan on counting 3 lines of text for every simple equation (single line) and 5 lines for every complicated equation (numerator and denominator).

2. **Estimating Length of Tables**

A. **First count** the longest line in each column across adding two characters between each column and one character between each word to obtain total characters.

<table>
<thead>
<tr>
<th>1-column table = up to 60 characters wide</th>
<th>2-column table = 61 to 120 characters wide</th>
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<tbody>
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<td>1-column table = up to 60 characters wide by:</td>
<td>2-column table = 61 to 120 characters wide by:</td>
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<td>17 lines (or less) = 158 word equiv.</td>
<td>17 lines (or less) = 315 word equiv.</td>
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<td>up to 34 lines = 630 word equiv.</td>
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<td>up to 51 lines = 945 word equiv.</td>
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<tr>
<td>up to 68 text lines = 630 word equiv.</td>
<td>up to 68 text lines = 1260 word equiv.</td>
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</table>

B. **Then count** the number of text lines (include footnote & titles)

C. Total Characters wide by Total Text lines = word equiv. as shown in the table above. Add **word equivalents** for each table in the column labeled "Word Equivalents."

3. **Estimating Length of Figures**

A. **First reduce** the figures to final size for publication.

**Figure type size can't be smaller than 6 point (2mm).**

B. **Use ruler** and measure figure to fit 1 or 2 column wide format.

<table>
<thead>
<tr>
<th>1-column fig. = up to 3.5 in.(88.9mm)</th>
<th>2-col. fig. = 3.5 to 7 in.(88.9 to 177.8 mm) wide</th>
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<td>up to 9 in.(228.6mm) high = 630 word equiv.</td>
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C. **Then use** a ruler to check the height of each figure (including title & caption).

D. Total Characters wide by Total Text lines = word equiv. as shown in the table above. Add **word equivalents** for each table in the column labeled "Word Equivalents."

| Total Tables/Figures: | 2682 |
| Total Words of Text: | 9669 |

| Total words and word equivalents: | 12351 |
| printed pages: | 10 |

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**Updated 1/16/03**

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**Figures:**

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updated 1/16/03
Reviewers' comments:

Editor: The reviews are positive. Reviewer #3 comments need to be addressed.

Reviewer #3: As indicated in my original review, I believe the manuscript provides a very interesting case study. (See original review.) I also indicated that the "AUTHORS SHOULD LOOK OVER THE ENTIRE MANUSCRIPT" and then drew attention to some of the items needing work. While the specific things I mentioned were addressed, some of the modifications still do not work well. Furthermore, the authors really do need to go over the whole thing. At the macro level, the manuscript is well organized and written, but many details of the writing need to be fixed. For example, the use of each semicolon should be reviewed, as well as the use of many of the commas (or the lack of use of commas at appropriate places)! See, for example, the structure of lines 1-5 of page 6, the last paragraph of page 9, and line 16 of page 23. Again, these are just examples. Also, minor wording changes are needed (e.g., lines 13-14 of the abstract---"policy...is two thirds..."--- and the sentence in lines 2-4 of page 3). These are just examples of the types of things that need to be fixed throughout. I know this sounds like nitpicking but the pervasive and glaring editing needs are extremely distracting (at least to me). Someone does need to review the final edited manuscript. Another detail: on line 13 of page 19, is the use of Municipal Rio Conchos as a name consistent with names used elsewhere, such as in table 2?

In the following section we have divided the Reviewer's #3 comments so each comment can be addressed adequately.

Reviewer #3: As indicated in my original review, I believe the manuscript provides a very interesting case study. (See original review.) I also indicated that the "AUTHORS SHOULD LOOK OVER THE ENTIRE MANUSCRIPT" and then drew attention to some of the items needing work. While the specific things I mentioned were addressed, some of the modifications still do not work well.

1) Furthermore, the authors really do need to go over the whole thing. At the macro level, the manuscript is well organized and written, but many details of the writing need to be fixed.
   Response: We have read the whole document and did our edits, the document has been proof edited once again.

2) For example, the use of each semicolon should be reviewed,
   Response: every semicolon has been reviewed and edited as needed.

3) as well as the use of many of the commas (or the lack of use of commas at appropriate places)!
   See, for example, the structure of lines 1-5 of page 6, the last paragraph of page 9, and line 16 of page 23. Again, these are just examples.
   Response: All the document has been reviewed to modified or include any commas.

4) Also, minor wording changes are needed (e.g., lines 13-14 of the abstract---"policy...is two thirds..."--- and the sentence in lines 2-4 of page 3). These are just examples of the types of things that need to be fixed throughout.
   Response: The wording of the document has been improved.
5) I know this sounds like nitpicking but the pervasive and glaring editing needs are extremely distracting (at least to me). Someone does need to review the final edited manuscript. 
Response: The first author has reviewed the final document entirely.

6) Another detail: on line 13 of page 19, is the use of Municipal Rio Conchos as a name consistent with names used elsewhere, such as in table 2?
Response: The authors have read and ensure that every Table and Figure match its description and content in the main document, we have checked for consistency between Tables, Figures and the main document.