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Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/thsj20

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Accepted author version posted online: 08 Jan 2014.Published online: 09 Dec 2014.

To cite this article: A. Robles-Morua, D. Che, A.S. Mayer & E.R. Vivoni (2014): Hydrological assessment of proposed reservoirs in the Sonora River Basin, Mexico, under historical and future climate scenarios, Hydrological Sciences Journal, DOI: 10.1080/02626667.2013.878462

To link to this article: http://dx.doi.org/10.1080/02626667.2013.878462

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Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 2015
http://dx.doi.org/10.1080/02626667.2013.878462

Hydrological assessment of proposed reservoirs in the Sonora River Basin, Mexico, under historical and future climate scenarios

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Received 28 June 2013; accepted 3 December 2013

Editor D. Koutsoyiannis

Abstract A semi-distributed hydrological model and reservoir optimization algorithm are used to evaluate the potential impacts of climate change on existing and proposed reservoirs in the Sonora River Basin, Mexico. Inter-annual climatic variability, a bimodal precipitation regime and climate change uncertainties present challenges to water resource management in the region. Hydrological assessments are conducted for three meteorological products during a historical period and a future climate change scenario. Historical (1990–2000) and future (2031–2040) projections were derived from a mesoscale model forced with boundary conditions from a general circulation model under a high emissions scenario. The results reveal significantly higher precipitation, reservoir inflows, elevations and releases in the future relative to historical simulations. Furthermore, hydrological seasonality might be altered with a shift toward earlier water supply during the North American monsoon. The proposed infrastructure would have a limited ability to ameliorate future conditions, with more benefits in a tributary with lower flood hazard. These projections of the impacts of climate change and its interaction with infrastructure should be of interest to water resources managers in arid and semi-arid regions.

Key words hydrological modelling; climate change; water infrastructure; decision support; flood control; northwest Mexico

Evaluation hydrologique des réservoirs proposés dans le bassin de la rivière Sonora (Mexique), sous scénarios climatiques historique et futurs

Résumé Un modèle hydrologique semi-distribué et un algorithme d'optimisation de réservoir ont été utilisés pour évaluer les impacts potentiels du changement climatique sur les réservoirs existants et proposés du bassin de la rivière Sonora, au Mexique. La variabilité climatique interannuelle, un régime de précipitations bimodal et les incertitudes du changement climatique représentent des défis pour la gestion des ressources en eau dans la région. Les évaluations hydrologiques ont été conduites pour trois produits météorologiques au cours d'une période historique et pour un scénario de changement climatique. Les projections historique (1990–2000) et futures (2031–2040) proviennent d'un modèle méso-échelle forcé avec des conditions aux limites d'un modèle de circulation générale sous scénario d'émissions élevées. Les résultats révèlent que, pour le futur par rapport à l'historique, les précipitations, les apports au réservoir, les hauteurs et les rejets sont nettement plus élevées. En outre, la saisonnalité hydrologique pourrait être modifiée avec des apports en eau plus précoces lors de la mousson nord-américaine. L'infrastructure proposée aurait une capacité limitée à améliorer les conditions futures, avec cependant l'avantage de limiter le risque d'inondation. Ces projections des impacts du changement climatique et de leur interaction avec les infrastructures devraient être intéressantes pour les gestionnaires des ressources en eau dans les régions arides et semi-arides.

Mots clefs modélisation hydrologique ; changement climatique ; infrastructures hydraulique ; aide à la décision ; lutte contre les inondations ; Nord-Ouest du Mexique

INTRODUCTION

In the 21st century, designing water resources infrastructure to meet growing demands or ameliorate flood risk will require accounting for the potential impacts of climate change on watershed response (e.g. Kundzewicz *et al*. 2008, Milly *et al*. 2008, Koutsoyiannis *et al*. 2009, Gleick 2010, Liuzzo *et al*. 2010, Forsee and Ahmad 2011, Johnson and Sharma 2011). The Intergovernmental Panel on Climate Change (IPCC) indicate that the southwest USA and northwest Mexico may experience a decrease in annual precipitation, primarily due to changes in the winter season (e.g. Christensen *et al*. 2007, Seager *et al*. 2007, Seth *et al*. 2011, Cavazos and Arriaga-Ramírez 2012), while less is known regarding the summertime North American monsoon (NAM, Cook and Seager 2013). Since this region experiences high inter-annual climate variability (Sheppard *et al*. 2002, Woodhouse *et al*. 2010), water resources management has been challenging, even in the absence of climate change, prompting the construction of large dams and aqueducts to store and transport multi-year storage amounts (see Sabo *et al*. 2010).

Less is generally known about the impacts of climate change on the water resources of northwest Mexico (Magaña and Conde 2000). For example, the border state of Sonora, Mexico, is experiencing a growing population, primarily in the capital of Hermosillo, which is exerting new water demands in the arid and semi-arid region. Explosive growth and a drought period have led to severe water rationing policies in the city over the past decade and to a continual search for new surface water or groundwater supplies (e.g. Eakin *et al*. 2007, Scott and Pineda-Pablos 2011). Figure 1 depicts a common situation in Hermosillo, where the local flood control and water supply reservoir in the Sonora River Basin (SRB) has fluctuated greatly in storage, but typically remains empty as water is stored in an upstream reservoir to avoid large evaporative and recharge losses. Understanding the impacts of climate change in this region is critical for designing adaptation strategies for flood and drought protection and sustainable water resources management.

To our knowledge, the potential impacts of climate change on the water resources of northwest Mexico have not been studied quantitatively. A common approach applied elsewhere is through the coupling of an atmospheric model, driven by greenhouse gas emissions scenarios, and a hydrological model capable of providing water resources supply estimates based on reservoir operations (e.g. Christensen and Lettenmaier 2007, Cayan *et al*. 2010). This coupling poses several technical challenges related to the mismatch in the spatiotemporal resolutions of each component. For example, Wilby (2010) and Kundzewicz and Stakhiv (2010) comment on the inadequacies of coarse (monthly, 100-km) general circulation models in providing inputs for water resources management models used for infrastructure planning and design activities. As a result, dynamical downscaling using mesoscale models can help translate coarse projections into higher-resolution meteorological forcing. This coupling requires reliable long-term networks of climate and hydrology

Fig. 1 Photographs of Abelardo L. Rodríguez Reservoir in Hermosillo taken from approximately the same location in: (a) October 1997 and (b) September 2012.

observations for evaluation of model projections (e.g. Praskievicz and Chang 2009, Wilby 2010). In developing countries with arid and semi-arid climates, challenges related to the availability of data and predictive models can be insurmountable, despite the urgent need for climate change assessments to inform water resources management. In Mexico, for example, the lack of climate information and modelling tools are cited as obstacles for decision-making (Browning-Aiken *et al.* 2007).

In this study, we address this challenge through the use of a set of modelling tools and long-term data sets in the SRB with the goal of informing water management decision-making in the region (e.g. Robles-Morua *et al.* 2014). Our approach is based on developing meteorological fields over historical (1990–2000) and future (2031–2040) periods by using boundary conditions from a general circulation model, the Hadley Centre Coupled Model version 3 (HadCM3), with a mesocale atmospheric simulation using the Weather Research and Forecasting (WRF) model. The high-resolution fields are then applied as forcing in a semi-distributed hydrological model applied and tested in the SRB. We analyse the impact of two proposed flood control reservoirs in the SRB in the context of the historical record and the climate change scenario. Our analysis is primarily focused on the inflows to, storage in and releases from the existing reservoirs (see Fig. 1) under the combined effects of climate change and upstream water resources infrastructure. This analysis is performed for an arid and semi-arid watershed with strong seasonality and limited carry-over storage from year to year (Robles-Morua *et al.* 2012). This study provides a foundation upon which to build stakeholder activities that test the utility of climate and hydrological models to provide actionable knowledge to water managers in the region, specifically in terms of assessing the usefulness of additional reservoirs under climate change scenarios.

METHODS

Study region and its hydroclimatic characteristics

The SRB, in the central portion of Sonora (Fig. 2), has an area of 20 648 km^2 that is classified as having an arid or semi-arid climate (Vivoni *et al.* 2007, 2010). The region has a bimodal precipitation regime, with a winter period consisting of frontal systems and a summer period with convective thunderstorms. Large elevation differences due to the presence of mountains result in a wide range of mean annual precipitation, from 350 mm/year near Hermosillo to 700 mm/year at higher elevations (Hallack-Alegria and Watkins 2007). As shown in Fig. 2(b), the 28-m elevation map derived from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) sensor reveals a 2.5-km difference from uplands to the coastal plain. Terrain and elevation variability in the SRB leads to large differences in the distribution of ecosystems (Watts *et al.* 2007, Méndez-Barroso *et al.* 2009, Forzieri *et al.* 2011). A 761-m MODerate Resolution Imaging Spectroradiometer (MODIS) land-use map using the University of Maryland (UMD) classification scheme (Fig. 2(c)) indicates that dominant ecosystem types are open, closed and wooded shrublands (72% of

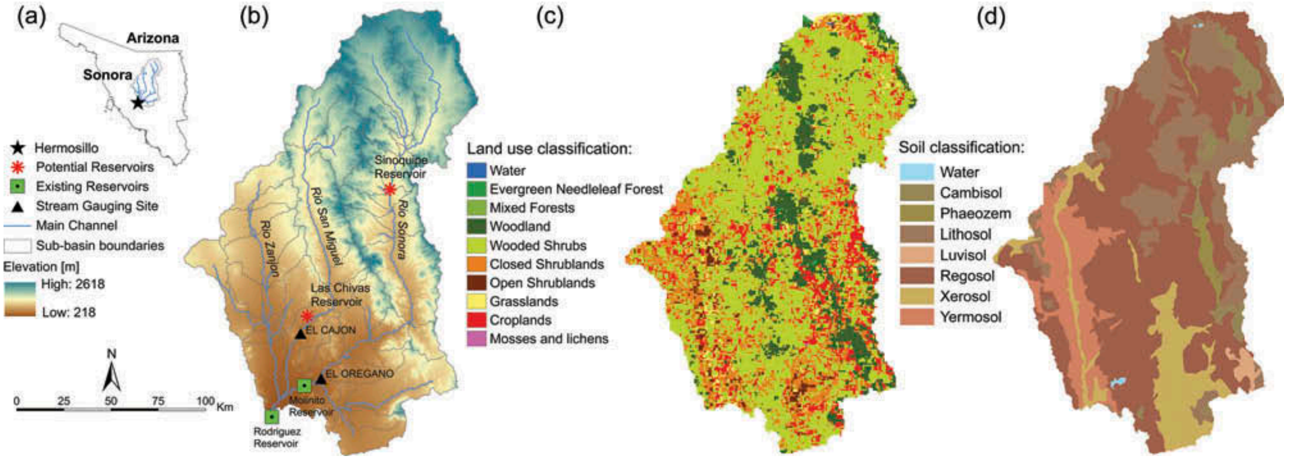

Fig. 2 (a) Sonora River Basin, Mexico; (b) 28-m ASTER elevation with hydrographic features; (c) 761-m MODIS land-use classification; and (d) 620-m INEGI soil classification.

total basin area), followed by woodlands (12%), and grasslands and croplands (14%). Soil distributions were obtained from a 620-m soil classification map from the Instituto Nacional de Estadística y Geografía (INEGI, Fig. 2(d)) aggregated to the major types without allowing in-class texture differences. The dominant soil type is Regosol (50% of total basin area), located in alluvial zones, followed by Lithosols (21%), usually located on steep hillslopes, while Xerosols and Yermosols account for a combined 22% of the SRB.

The SRB flows from northeast to southwest following the topographic variability imposed by several mountain ranges until its final destination in the Abelardo L. Rodríguez reservoir (Figs 1 and 3, named "Rodríguez" here) adjacent to Hermosillo. Since dam construction in 1945–1948, there have been few releases to the Sonora River. With a population of ~750 000 that is growing at an annual rate of 3% (CONAPO 2008), Hermosillo relies on surface water and groundwater resources from the SRB (Scott and Pineda-Pablos 2011). Of the three tributaries in the SRB (San Miguel, with 4230 km^2 of drainage area; Zanjón, with 4308 km^2 of drainage area; and Sonora, with 9350 km^2 of drainage area, Fig. 2(b)), only the Sonora River has an upstream reservoir, the Rodolfo Félix Valdéz Reservoir. This reservoir, known as "Molinito", was built in 1991–1992. Both reservoirs were designed for flood control and within-year storage, but water demands lead to extractions during seasons when water is available. Two stream gauging sites managed by the Comisión Nacional del Agua (CONAGUA) provide daily, manually-obtained observations in the San Miguel ("El Cajón") and Sonora rivers ("El Oregano", upstream of Molinito Reservoir). Two additional reservoirs are proposed in the SRB as part of the SONORA Sistema Integral (SI) project, to be used primarily for flood control upstream of Molinito, and in the San Miguel River (Scott and Pineda-Pablos 2011). While the SRB is not the major water source for Hermosillo, it remains an important asset as a seasonal water supply and a source of groundwater to well fields located downstream of the basin (CEA 2005).

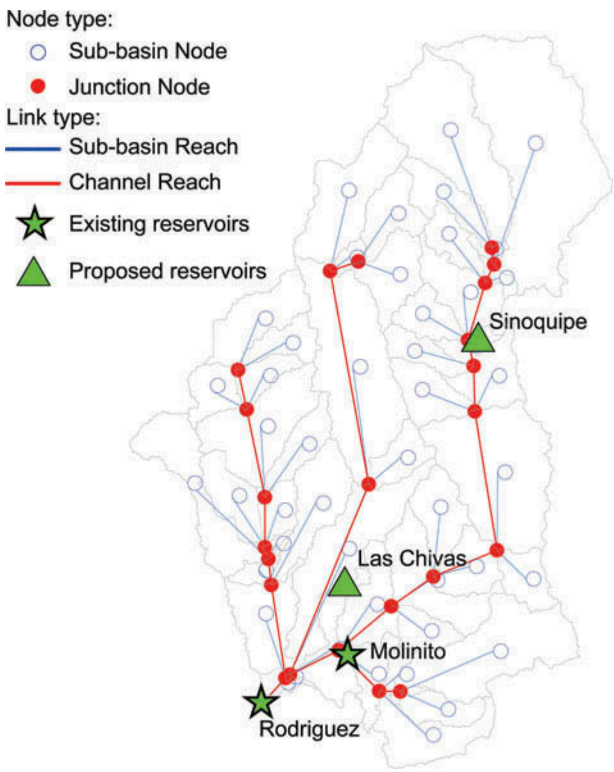

Fig. 3 Schematic representation of the HEC-HMS model in the SRB.

Meteorological data products for historical and future periods

The selection of meteorological forcing is critical for hydrological predictions, yet limited guidance exists for this choice in arid and semi-arid regions of northwest Mexico. As a result, we compared meteorological variables in the SRB from three different products: (a) a ground-based network (named "GAUGES" here) available from 1980–2010; (b) a re-analysis dataset from the North American Land Data Assimilation System (NLDAS) from 1990–2010; and (c) mesoscale atmospheric simulations from the WRF model over a historical (1990–2000) and a future (2031–2040) period. The GAUGES product is obtained from 30 daily raingauge sites managed by CONAGUA in and around the SRB and includes an interpolation using Thiessen polygons (or nearest neighbourhood). Large distances between stations can result in a poor spatial representation that may overestimate precipitation in the SRB (Robles-Morua *et al*. 2012). A subset (24 of 30) of CONAGUA sites also report daily pan evaporation (mm/d), used here for land surface evapotranspiration and reservoir evaporation estimates.

NLDAS precipitation fields are available at hourly time periods, aggregated here to the daily scale, and at a spatial resolution of 12 km (Mitchell *et al*. 2004). Over Mexico, NLDAS precipitation is an observational dataset obtained from a daily US–Mexico raingauge analysis (Higgins *et al*. 2000) that is temporally disaggregated based on an hourly remote sensing product (Joyce *et al*. 2004). For this study, we used the raw NLDAS precipitation dataset without applying a local raingauge correction, as performed in Robles-Morua *et al*. (2012), to assess the capabilities of the native NLDAS product relative to the GAUGES dataset. NLDAS is a recent product for climate and hydrology studies and few studies have assessed it relative to ground-based data in Mexico. Two additional meteorological variables from NLDAS, daily-averaged solar radiation (W/m^2) and air temperature (°C), were used to estimate land surface evapotranspiration and reservoir evaporation at 12-km resolution and then aggregated to the sub-basin resolution.

The application of the WRF model (Skamarock *et al*. 2005) provides dynamically-downscaled, hourly precipitation, solar radiation and air temperature fields at 10-km resolution that were aggregated to the daily scale over the historical and future periods. Wi *et al*. (2012) describe the downscaling approach with the HadCM3 model boundary conditions under the A2 emissions scenario and provide descriptions of the WRF model set-up. Wi *et al*. (2012) first conducted a WRF downscaling simulation at a 35 km, 6-h resolution over the coterminous United States and northern Mexico using HadCM3 boundary forcings. Based on these fields, a second downscaling step was performed with WRF to provide outputs at 10 km, 1-h resolution over a more limited domain (28°–37°N, 105°–116°W, Robles-Morua *et al*. 2011). As described by Wi *et al*. (2012), the downscaling approach utilized spectral nudging (Miguez-Macho *et al*. 2005) on zonal and meridional winds, air temperatures and geopotential height fields at high elevations above the surface to retain the synoptic-scale variability of the HadCM3 model. The A2 scenario from IPCC (2007) contains relatively high greenhouse gas emissions that have been used in climate change assessments previously (Mearns *et al*. 2012). Dominguez *et al*. (2010) showed that the HadCM3 model performed well in the southwest USA and portions of northwest Mexico by capturing precipitation and temperature realistically, including the inter-annual variability from El Niño Southern Oscillation (ENSO). Furthermore, prior efforts also show that HadCM3 has good skill in capturing inter-annual variability related to ENSO and its link with precipitation (e.g. van Oldenborgh *et al*. 2005, Johnson *et al*. 2011). Nevertheless, it is important to note the WRF simulations represent only one model-specific projection from which meteorological variables were obtained for hydrological model forcing. The future period (2031–2040) selected for dynamical downscaling with WRF is a 10-year time slice representative of the early 21st century as reproduced by the HadCM3 model under a high (A2) emissions scenario.

Hydrological and reservoir model application, calibration and validation

The hydrological model used in this study is the US Army Corps of Engineers (USACE) Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), version 3.5. The model has been extensively applied worldwide, including in the assessment of climate change impacts (e.g. Ebrahim *et al*. 2013, Meenu *et al*. 2013). The HEC-HMS model was designed to simulate rainfall–runoff processes in a wide variety of watersheds under different levels of data availability based on the concept of sub-basins derived from the channel network morphology (Scharffenberg and Fleming 2010). Based on the existing data products and our understanding of the hydrological system (e.g. Vivoni *et al*. 2010, Robles-Morua *et al*. 2012), we selected hydrological process equations to depict the rainfall–runoff transformation (Table 1). For the sub-basin processes, we chose the

Table 1 Hydrological processes selected in the HEC-HMS model (Feldman 2000).

Model process	Description	Parameters	Daily inputs
Rainfall interception	Canopy storage method	Leaf Area Index (LAI)	Precipitation (P)
Surface detention	Depression storage method	Mean slope (S); depression storage depth (D_d)	Precipitation (P)
Evapotranspiration	Priestley-Taylor method	Crop coefficient (K_c); dryness coefficient (K_d)	Solar radiation (R_s); Air temperature (T_a)
Infiltration	Soil moisture accounting scheme	Soil storage depth (D_s); maximum soil infiltration rate ($I_{\max}$)	–
Sub-basin routing	Kinematic wave method	Sub-basin reach length (L), mean slope (S) and roughness (n)	–
Channel routing	Muskingum-Cunge method	Channel reach width (W), length (L), mean slope (S) and roughness (n)	–

canopy storage method for rainfall interception, a surface depression method, the soil moisture accounting scheme to track infiltration losses and soil water movement, and the Priestley-Taylor approach to estimate evapotranspiration. Excess rainfall was converted into surface runoff using the kinematic wave method which routes runoff through each sub-basin area. In the channel network, runoff was routed downstream using the finite-difference Muskingum-Cunge method. Reservoirs located on the channel network were simulated using a mass balance approach and were subject to evaporation losses and operational rules.

A reservoir optimization algorithm was applied at the two existing reservoirs (Rodríguez and Molinito) using the nonlinear programming-based general algebraic modelling system (GAMS; Brooke *et al.* 1998), which was applied to estimate reservoir releases for the historical period, since these records are unavailable, and for the future period. For the historical period, releases were obtained by matching computed reservoir storage against daily, observed reservoir storage records (CONAGUA) using the root mean square error (RMSE) as an objective function. For the future period, the objective function maximized the total reservoir releases over the entire future period. For both the historical and future periods, the constraints described in the Appendix were applied to avoid spillway overflow and maintain upper and lower limits of pool elevations that matched the CONAGUA operational rules.

Reservoir design parameters, including spillway length, outlet structure, and elevation-area relation, were obtained from CONAGUA and applied in each case. For both the historical and future periods, reservoir operations were based on flood control purposes without considering water supply extractions from Molinito Reservoir, under the assumption that these extractions were small relative to evaporation losses. The optimization algorithm was used in a coupled fashion with HEC-HMS for the Molinito Reservoir (1993–2010) and in an uncoupled manner at the Rodríguez Reservoir (1980–2010), as in McEnroe (2010). Reservoir releases computed in GAMS for Molinito were fed back to HEC-HMS to complete downstream simulations (i.e. a coupled operation). At the Rodríguez Reservoir, GAMS also computed downstream releases; however, these releases were not fed back to HEC-HMS (i.e. an uncoupled operation), since the study area did not extend downstream of the reservoir.

The HEC-HMS model domain was generated from terrain analyses performed on the 28-m ASTER digital elevation model (DEM) using HEC-GeoHMS (Fleming and Doan 2010), yielding 48 individual sub-basins in the SRB. Figure 3 presents the distribution of sub-basins and their internal reaches, the channel network composed of river reaches and junctions, and the locations of existing and proposed upstream reservoirs (“Sinoquipe” and “Las Chivas”). Sub-basin properties, including total area and mean slope, were calculated for inputs to the hydrological process equations. Table 2 presents a set of statistical metrics describing sub-basin properties and parameter values in the model representation. Similarly, vegetation and soil properties, derived from the land-use and soil texture classifications and shown in Fig. 2, were aggregated to the sub-basin extents based on a spatial weighted-average of parameter values. Channel properties, including reach length and mean slope, were extracted from the DEM and used to parameterize the sub-basin and channel reach routing equations. The two proposed reservoirs were placed at sites identified by the SI infrastructure plan (cf. Cruz-Varela and Monge-Martínez 2012). Due to the absence of engineering plans, we applied

Table 2 Statistical properties of model parameters.

Parameter	Unit	Mean	Max.	Min.	SD
Sub-basin area	km^2	430	2310	4	433
Sub-basin reach length	m	23 477	100 379	1082	23 924
Sub-basin reach mean slope	m/m	0.018	0.059	0.004	0.011
Canopy storage depth	mm	1.57	3.94	0.73	0.57
Depression storage depth	mm	1.03	3.91	0.02	0.68
Maximum soil infiltration rate	mm/h	1.80	4.57	0.41	0.90
Soil storage depth	mm	500	500	500	0
Channel width	m	10	10	10	0
Channel reach length	m	24 273	92 977	1875	23 076
Channel reach mean slope	m/m	0.003	0.005	0.0004	0.0013
Manning’s roughness coefficient	–	0.035	0.035	0.035	0

the same flood-control operational rules of Molinito Reservoir at each proposed site, though we adjusted evaporation to local conditions.

The set of process equations selected for the HEC-HMS model required parameters and initial conditions for each of the sub-basins and reaches (Table 1). Prior modelling studies in the SRB (Vivoni *et al.* 2010, Robles-Morua *et al.* 2012, Méndez-Barroso *et al*. 2014) provided initial estimates of the soil, vegetation and routing parameters. Due to the arid and semi-arid climate, we assumed that the canopy, depression and soil water storages at the beginning of the simulation were negligible (Vivoni *et al.* 2010). These storage components equilibrated within a year during longer simulation runs. We used a parameter optimization routine in HEC-HMS to calibrate the hydrological model with respect to the observed daily stream discharge (Q, m^3/s) at the two gauging sites, upstream of the reservoirs. The calibration (1980–1989) and validation (1990–1999) periods were forced with daily GAUGES precipitation and pan evaporation. This approach allowed the model application to be based on long-term, ground data considered valid by local water managers. The optimization method selected for the calibration was the Nelder-Mead search algorithm with a peak-weighted RMSE as the objective function (Feldman 2000).

We calibrated the canopy and depression storage depths and maximum soil infiltration rate parameters as these parameters were poorly constrained at the sub-basin scale from prior modelling efforts (Table 2). Figure 4 (top row) presents the results of the calibration for daily records at the El Cajón (San Miguel River) and El Oregano (Sonora River) stream gauging sites. The HEC-HMS simulations captured well the seasonality of stream discharge in the SRB in response to winter and summer rainfall, with the majority of runoff occurring during the NAM (Robles-Morua *et al.* 2012). Furthermore, the peak events that are more significant for the operation of the flood control dams were simulated very well. The stream discharge RMSE during the calibration period was 5.46 and 18.90 m^3/s at El Cajón and El Oregano, respectively. As expected, the model performance deteriorated in the validation period at each site (Fig. 4, bottom row), with RMSE of 36.00 and 53.50 m^3/s, respectively. Simulations at El Cajón were superior due to the smaller upstream area and better rainfall representation by available gauges. Three additional metrics, correlation coefficient (CC), volume bias (B) and mean absolute error (MAE), are presented in Table 3 along with mean stream discharge values for each period and gauging site. Overall, the metric values indicate adequate

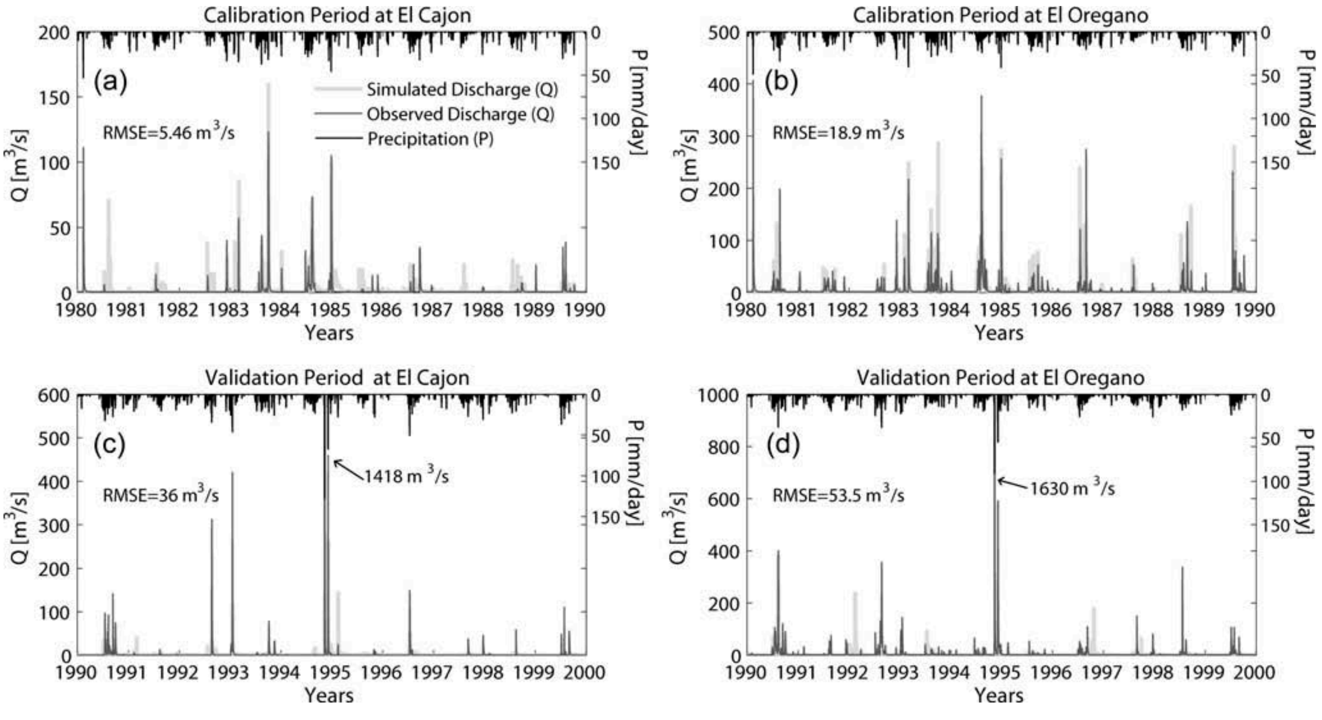

Fig. 4 Comparison of daily observed and HEC-HMS simulated stream discharge at (a, c) El Cajón and (b, d) El Oregano for the calibration (top row) and validation (bottom row) periods along with the daily basin-averaged precipitation from GAUGES. Discharge RMSE values are shown in each.

Table 3 Observed and simulated mean stream discharge (m^3/s) for calibration (1980–1990) and validation (1990–2000) periods at two gauging sites with model performance metrics following definitions in Vivoni *et al.* (2006). CC: correlation coefficient (-), B: bias (-), MAE: mean absolute error (m^3/s) and RMSE: root mean square error (m^3/s).

Period	Gauging site	Mean discharge		Metric			
		Observed (m^3/s)	Simulated (m^3/s)	CC (−)	B (−)	MAE (m^3/s)	RMSE (m^3/s)
Calibration	El Cajón	1.74	1.73	0.63	0.99	1.48	5.46
	El Oregano	4.84	6.73	0.55	1.39	5.57	18.90
Validation	El Cajón	1.40	3.61	0.51	1.57	3.17	36.00
	El Oregano	2.21	7.76	0.43	1.52	7.82	53.50

model performance given the range of uncertainties involved in the simulations, including: (a) precipitation errors in GAUGES, (b) discharge measurement errors and omissions in CONAGUA records, (c) model structural errors related to process equations, and (d) model parameter uncertainties and their interactions. The calibrated parameters were then applied to the historical (1990–2000) period with the GAUGES, NLDAS and WRF forcing and to the future (2031–2040) period with the WRF climate change scenario.

Numerical experiments with proposed reservoirs under historical and future climate

We conducted simulations with HEC-HMS and GAMS for historical and future periods using the applicable meteorological forcings. The long (~10-year) runs began with identical initial conditions, had similar calibrated parameters and utilized the same reservoir operational rules. The only variations among the experiments were the spatial resolution, timing and magnitude of the precipitation and evapotranspiration forcing. Comparison of the three products and two periods (historical and future) allowed understanding of the impacts of the spatial resolution, product accuracy and climate change on the hydrological simulations of the SRB. Superimposed on this, we conducted a set of simulations with the existing reservoirs (named 'Base Case') and another with the addition of the two proposed reservoirs (named 'Base Case + Reservoirs'). Comparison of the reservoir scenarios allowed quantifying the impact of proposed infrastructure on water resources under the historical and climate change scenarios. As a result, this comparison allows an evaluation of the role of climate change with respect to changes in the water resources system, as advocated by Koutsoyiannis *et al.* (2009) and Wilby (2010).

RESULTS AND DISCUSSION

Comparison of meteorological forcings for historical and future periods

Due to their independent nature, the meteorological products yielded variable inputs to the HEC-HMS simulations. Figure 5 shows the differences in the spatial resolution and magnitude of the mean annual precipitation in the historical period (1990–2000). Clearly, the sparse raingauge network and its Thiessen polygon

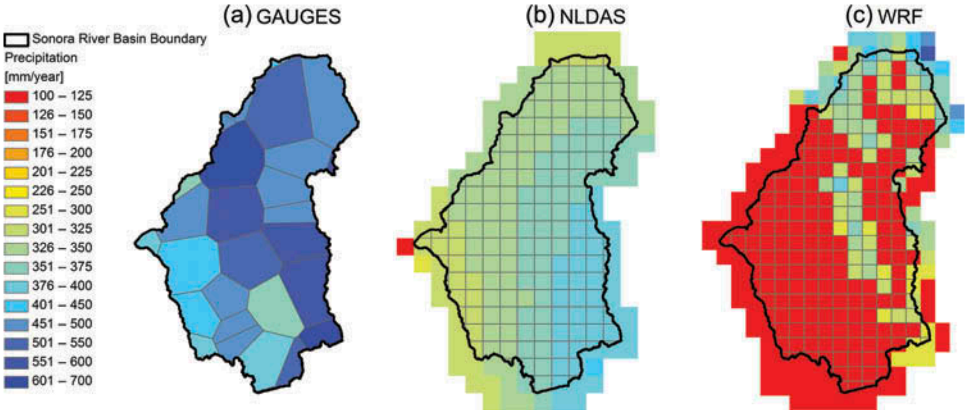

Fig. 5 Mean annual precipitation (1990–2000) from (a) GAUGES; (b) NLDAS; and (c) WRF.

interpolation (GAUGES) results in a coarser input to HEC-HMS as compared to the other products. In contrast, NLDAS and WRF provide high-resolution inputs (12 and 10 km) to the HEC-HMS model. However, an aggregation within each sub-basin using a weighted-average is also applied prior to the model simulations. At the scale of the SRB, the GAUGES and NLDAS demonstrate mean annual precipitation in the range of 300 to 700 mm/year (486 ± 74 and 350 ± 26 mm/year, respectively), consistent with estimates by Vivoni *et al.* (2010) and Forzieri *et al.* (2011). Nevertheless, the detailed pattern of NLDAS has a more realistic representation of precipitation differences between valley bottoms and mountains. This distinction is not present in GAUGES since most raingauge sites are located near river valleys. While the WRF historical product also has precipitation patterns that conform to topographic controls, a strong negative bias is evident in the SRB (Fig. 5) as compared to GAUGES and NLDAS, with a mean annual precipitation ranging from 100 to 500 mm/year in the SRB (249 ± 79 mm/year). This negative bias is consistent with Castro *et al.* (2012) who found that a dynamical downscaling approach using WRF underestimated observed precipitation in this region during the summer time. Based on the analysis of Cavazos and Arriaga-Ramírez (2012), it is likely that the underestimation in the historical WRF product is related to the boundary conditions specified by HadCM3, which for the region exhibit a precipitation shift from summer to autumn, relative to observed precipitation patterns. In the spirit of performing a hydrological comparison of the native products, we did not correct the precipitation bias in the WRF historical period.

A comparison of the basin-averaged annual precipitation for the three meteorological products is shown in Fig. 6 for the historical extents in each case and for the future period in the case of WRF (inset). Note the large inter-annual variability in precipitation for the SRB across all products, consistent with Brito-Castillo *et al.* (2003) and Arriaga-Ramírez and Cavazos (2010). Despite some year-to-year differences between GAUGES and NLDAS, the two products match fairly well during the overlapping period and have similar annual averages of 450 and 431 mm/year. As noted previously, WRF underestimates annual precipitation during the overlapping period, but exhibits trends that are consistent with other products, in particular the drier-than-average conditions in 1994–2000. Of notable importance are the predictions of increased annual precipitation (200 to 800 mm/year, with an average of 466 mm/year) in the future period (2031–2040) resulting from dynamically downscaling the HadCM3 model under the A2 emissions scenario. As compared to the historical period, simulations during 2031–2040 have 1.8 times more annual precipitation on average. Note also that the inter-annual variability remains high in the future and that annual precipitation for any year in the future period still falls in the range of historical data from GAUGES and NLDAS, except possibly for 2032.

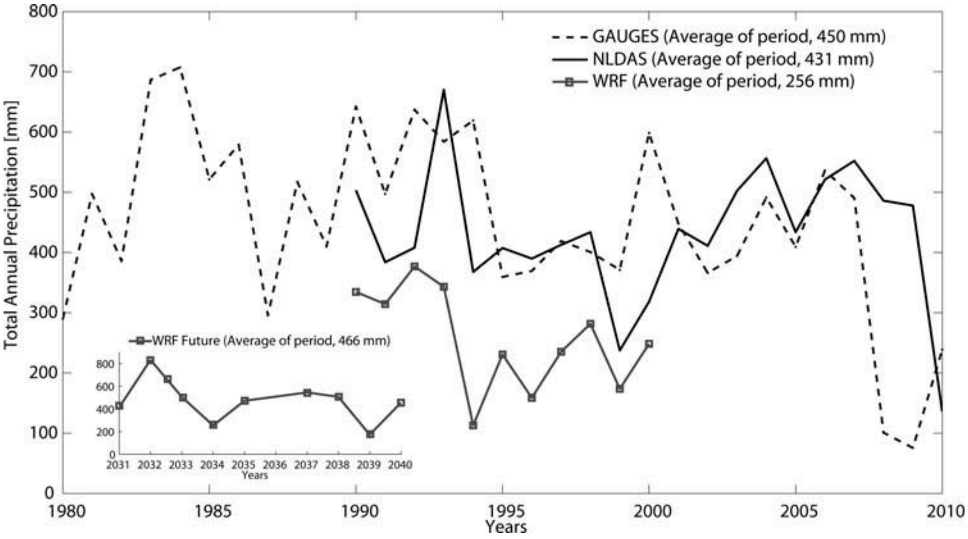

Fig. 6 Basin-averaged annual precipitation (mm) for the three meteorological products over historical extents. Inset shows the WRF annual precipitation over the future period.

Reservoir analyses for historical and future periods under infrastructure scenarios

Figure 7 presents a comparison of the inflows to Molinito (top row) and Rodríguez (bottom row) reservoirs over the historical (1990–2000) and future (2031–2040) periods for the Base Case (existing reservoirs) and Base Case + Reservoirs (existing and proposed reservoirs) scenarios. For each case, daily stream discharge (*Q*, m^3/s) over multiple years is shown as a probability exceedence plot where large inflows (i.e. floods) have low probabilities and small inflows (i.e. baseflow) have high probabilities of exceedence. As expected, the addition of upstream reservoirs (Sinoquipe and Las Chivas) reduces the reservoir inflows to Rodríguez Reservoir over most of the range of exceedence probabilities, as shown by a comparison of solid and dashed-dotted lines. The upstream Sinoquipe Reservoir, however, would only attenuate inflows into Molinito Reservoir below a certain threshold that depends on the meteorological forcing product (e.g. less than 40 m^3/s and 100 m^3/s for GAUGES and NLDAS), implying that its flood control potential is quite limited (cf. Fig. 4). Interestingly, the Las Chivas Reservoir on the San Miguel River appears to have a higher impact at Rodríguez Reservoir, in particular by reducing flood events of low exceedence probability. This is due to the imposition of flood control operating rules on the unregulated tributary, which tends to generate large floods (e.g. Vivoni *et al*. 2007).

Despite similarities in basin-averaged annual precipitation, GAUGES and NLDAS have sharply different inflows into Molinito Reservoir over the full range of stream discharge and for small floods and baseflow conditions into Rodríguez Reservoir. As observed by Robles-Morua *et al.* (2012) for the Sonora River main stem, this result implies that rainfall is delivered as fewer, more intense events in GAUGES that generate higher stream discharge as compared to NLDAS. For the entire SRB, however, NLDAS matches GAUGES well for stream discharge greater than 100 m^3/s, indicating precipitation in other tributaries can be as intense in NLDAS. In contrast, the WRF historical case underestimates reservoir inflows relative to GAUGES across all exceedence probabilities, but overlaps with NLDAS well at Molinito Reservoir. As a result, the negative precipitation bias in WRF propagates to stream discharge in the entire SRB. Higher precipitation in the future period increases inflows to both reservoirs across all exceedence probabilities, except baseflows of 2–3 m^3/s, relative to the WRF historical period. More interestingly, future inflows to Molinito Reservoir increase beyond GAUGES and NLDAS for stream discharges greater than 20 m^3/s, while future inflows to Rodríguez Reservoir match the GAUGES and NLDAS historical simulations fairly

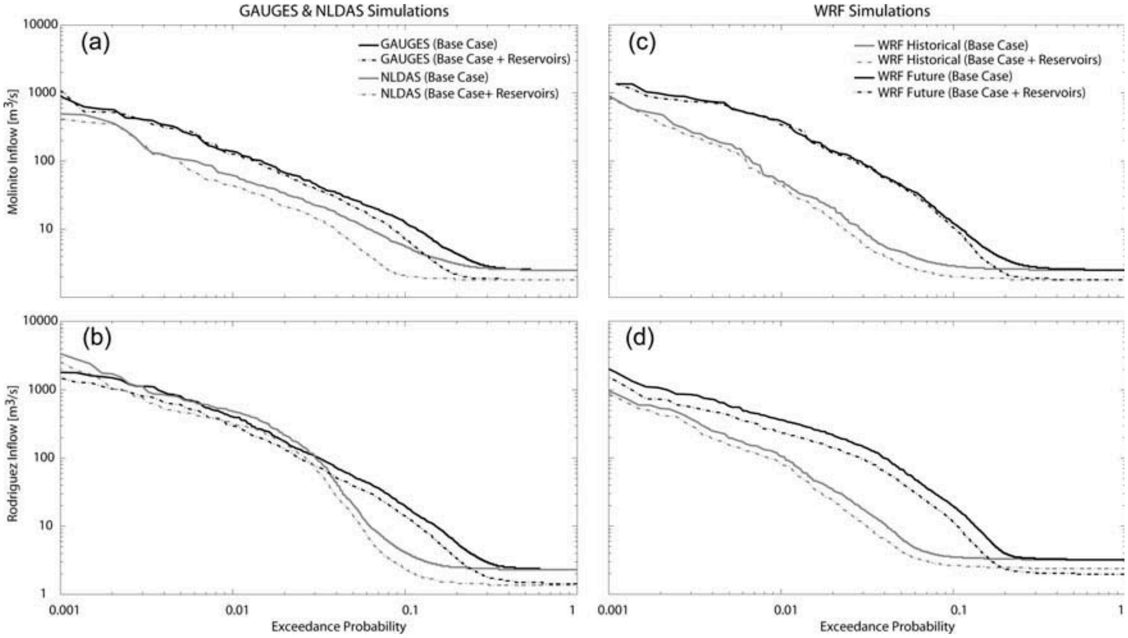

Fig. 7 Probability exceedence of reservoir inflows for (a, b) GAUGES and NLDAS simulations; and (c, d) WRF simulations at Molinito (top row) and Rodríguez (bottom row) reservoirs.

well. This result indicates that the future flood hazard increases proportionally more in the main stem of the Sonora River, where the Sinoquipe Reservoir would have a limited impact, as compared to the rest of the SRB.

We explore this trend further by inspecting pool elevations for the different meteorological products across the reservoir scenarios in Fig. 8. Pool elevation (m a.s.l.) or water height is shown in the form of a probability of exceedence curve and compared to observations made by CONAGUA. Note that HEC-HMS and GAMS simulations for GAUGES match the pool elevation data well during the historical period, with low exceedence probability levels 2–6 m below the dam top elevation. The addition of upstream reservoirs reduces pool elevations by up to 3 m, in particular when reservoirs are near full capacity, across all historical meteorological products. Interestingly, the pool elevations in the future period (2031–2040) are significantly higher than the WRF historical period, with heights near the maximum allowable levels for exceedence probabilities less than 0.1 (or for the top 10%). Future pool elevations in Molinito Reservoir either exceed or match historical GAUGES for low and high storage, indicating pool levels will be 2–6 m higher in the future, during 90% of the time. Similarly, future pool elevations in the Rodríguez Reservoir would be 1–3 m higher as compared to GAUGES over most of the time periods. Upstream reservoirs have a limited impact on reservoir storage in the future, with a small reduction at high exceedence probabilities. As a result, higher future precipitation in the SRB leads to greater storage in the existing system, with Molinito Reservoir exhibiting maximum allowable levels over more time as compared to Rodríguez Reservoir. This result indicates that the higher future flood potential in the Sonora River can be effectively stored at Molinito Reservoir, at least under the current operational rules and releases.

Cumulative release volumes (10^6 m^3) from Molinito Reservoir are shown in Fig. 9 for the different meteorological products and reservoir scenarios. The inclusion of an upstream reservoir at Sinoquipe reduces the cumulative releases by a larger proportion for GAUGES as compared to NLDAS and WRF during the historical period, primarily due to the larger floods generated in the years 1994 and 2000. Since inflows are nearly similar with and without the Sinoquipe Reservoir (Fig. 7), variations in releases are due to operational rules at Molinito Reservoir that maintain pool elevations at or below the maximum allowable level (ST_{max}, Appendix). For the future period (2031–2040), HEC-HMS and GAMS simulations of the WRF product indicate more than a doubling in cumulative releases from Molinito Reservoir. The Sinoquipe Reservoir would reduce cumulative release volumes by a small

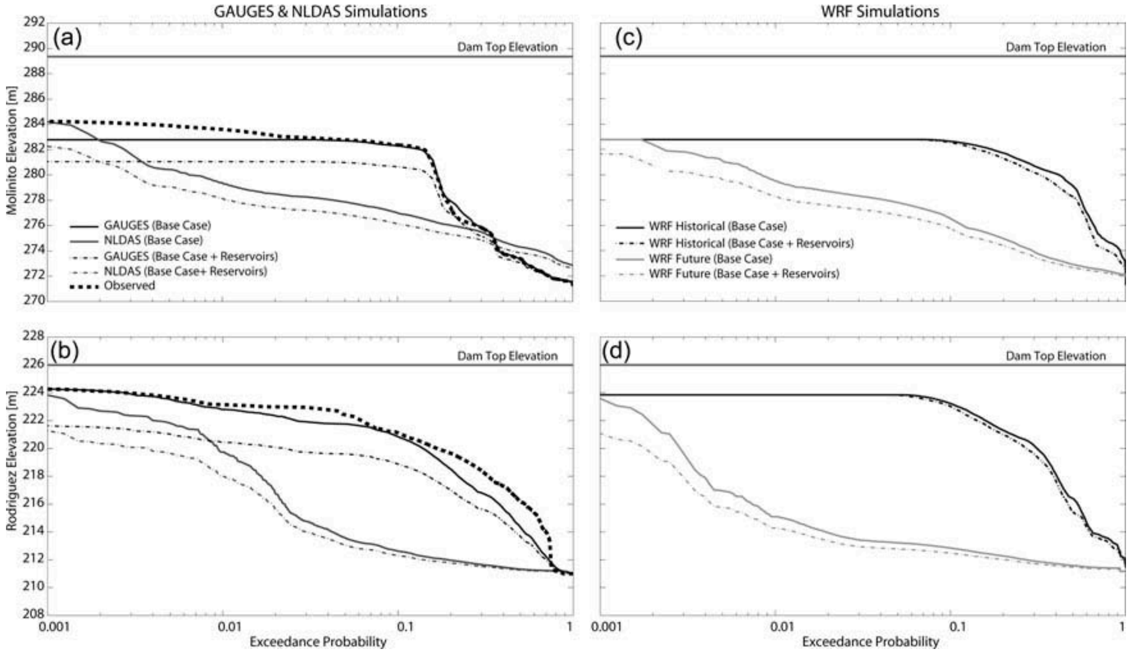

Fig. 8 Probability exceedence of pool elevations for (a, b) GAUGES and NLDAS simulations; and (c, d) WRF simulations at Molinito (top row) and Rodríguez (bottom row) reservoirs.

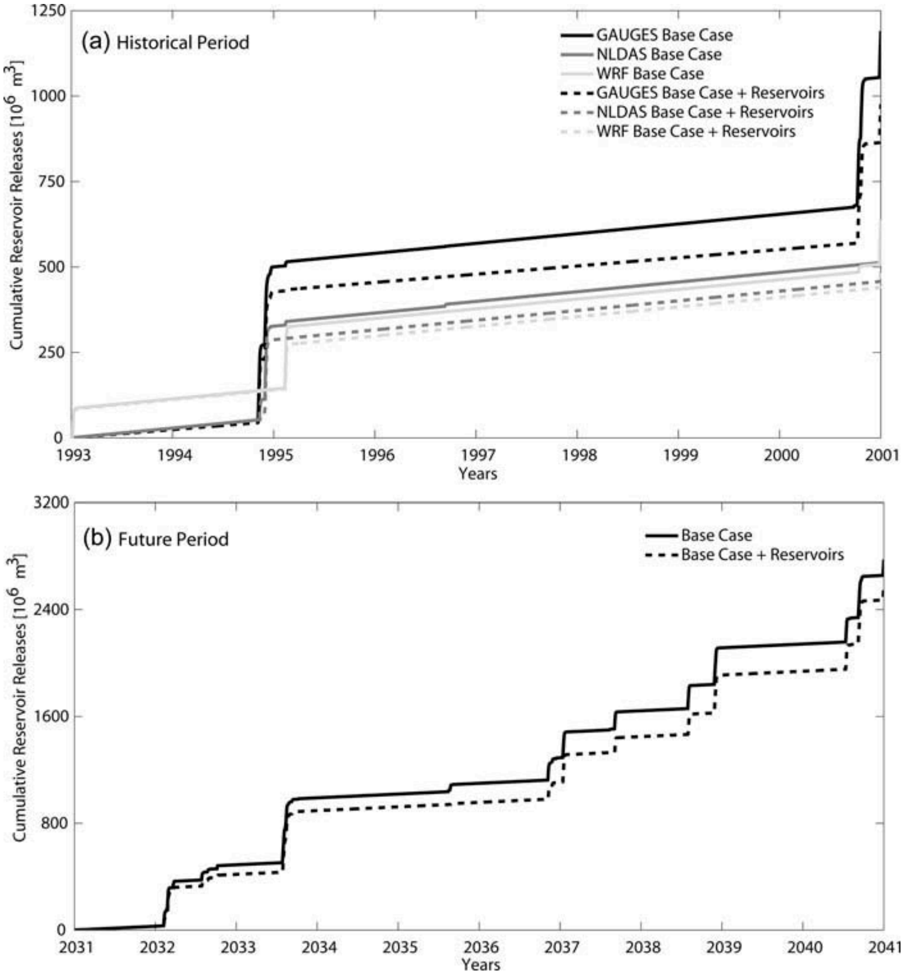

Fig. 9 Cumulative release volumes at Molinito Reservoir for (a) historical; and (b) future periods.

quantity, which affects the high exceedence probabilities of pool elevation in the downstream Rodríguez Reservoir (Fig. 8). This result indicates the lack of utility of this particular reservoir under the climate change scenario. More interesting is that Molinito Reservoir operates near full capacity due to higher inflows, yet still allows downstream releases that combine with stream discharge from other tributaries to fill Rodríguez Reservoir.

Seasonality in reservoir storages for historical and future periods

The bimodal precipitation regime in the SRB leads to reservoir storage increases in the winter and summer seasons (Brito-Castillo *et al*. 2003). Figure 10 diagnoses the impact of climate change and upstream reservoirs on the monthly storage (10^6 m^3) of Molinito Reservoir obtained by averaging each month over the corresponding periods. GAUGES, NLDAS and WRF historical simulations all show higher reservoir storage from January to March, but vary in magnitude due to differences in precipitation among the products. The WRF matches well the timing of reservoir increases in the winter as compared to GAUGES. In contrast, the reservoir storage increases from August to October in GAUGES and NLDAS are delayed in the WRF historical simulation, instead occurring in October and November. This hydrological evidence indicates that WRF underestimates precipitation in both seasons and exhibits a time delay of one to two months, consistent with other studies (e.g. Gutzler *et al*. 2009, Seth *et al*. 2011). The time shift in the reservoir storage is due to the delay in precipitation (from summer to autumn) found within the HadCM3 boundary conditions, as shown by Cavazos and Arriaga-Ramírez (2012).

In the future period, the simulated increases in annual precipitation express themselves as higher

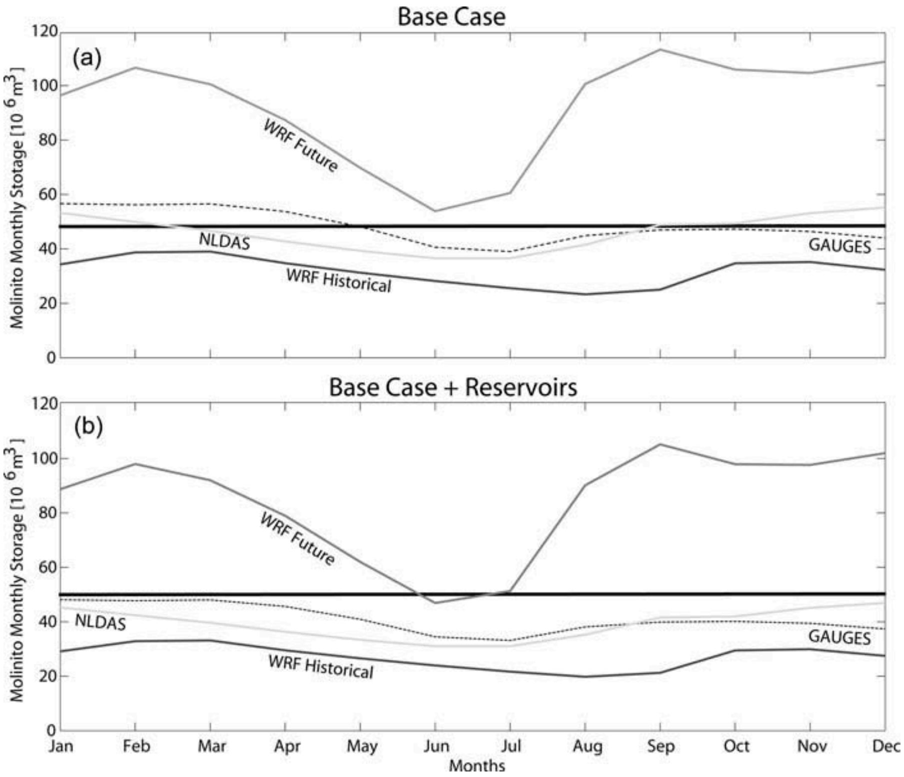

Fig. 10 Monthly Molinito Reservoir storage for historical and future periods under (a) Base Case; and (b) Base Case + Reservoir scenarios. Solid horizontal line is GAUGES annual average.

reservoir storages during both winter and summer, with a clear shift toward earlier increases in precipitation and reservoir storage during the NAM (July–October). Considering the negative bias and delayed NAM onset in the WRF historical period, these results suggest that the SRB may experience a substantially wetter future that leads to higher reservoir storages during most of the year, with the exception of April–July. Clearly, this does not account for variations in the operational rules that may be implemented in the future, including larger water extractions. The addition of an upstream reservoir reduces historical and future monthly storage in Molinito Reservoir without impacting seasonality.

SUMMARY AND CONCLUSIONS

This study used a semi-distributed hydrological model and a reservoir optimization algorithm to evaluate the hydrological impacts of climate change and proposed reservoirs in the Sonora River Basin, Mexico. We evaluated three meteorological products during a historical period (1990–2000) and a single climate change scenario during a future period (2031–2040) in concert with the proposed water infrastructure plans. Historical simulations driven with ground-based forcing were calibrated and tested with stream gauging data at two channel sites and pool elevation data in two reservoirs yielding an adequate model performance. Analyses conducted on reservoir inflows, pool elevations, release volumes and seasonal storages for the meteorological and infrastructure scenarios revealed the following:

1. The future period contained a significantly higher amount of precipitation relative to the historical simulation with the dynamical downscaling approach. This trend led to projections of higher reservoir inflows, pool elevations and releases from the existing reservoirs. As a result, the future scenarios lead to pool elevations and releases in existing reservoirs that greatly exceed those observed historically, indicating a significant shift in current water system behaviour.
2. Proposed, upstream reservoirs in the SRB would have a limited impact on the inflows, pool elevations and releases of downstream reservoirs under historical and future periods. The Las Chivas Reservoir proposed for the San Miguel

River would add a small degree of flood control over what is currently available through the Rodríguez Reservoir, while the higher flood hazard in the Sonora River main stem would not be ameliorated with the addition of Sinoquipe Reservoir, since Molinito Reservoir has sufficient capacity to handle additional stream discharge.

3. An analysis of the reservoir storage seasonality showed the impact of the bimodal precipitation regime in the SRB during historical and future periods. Large increases in Molinito Reservoir storage in the future period may occur during both winter and summer seasons, with a shift toward earlier water supply during the North American monsoon. A new upstream reservoir would not substantially alter the seasonal differences induced by climate change.

This study is based on one climate change scenario over a short and relatively near time period (2031–2040) using the HadCM3 model boundary conditions, A2 emissions scenario and dynamical downscaling using WRF, thus limiting its generality with respect to future meteorological forcing. Nevertheless, the approach taken here allows for a more realistic use of climate change projections in water resources management, since the dynamical downscaling offers improvements in the representation of orographic precipitation, as shown by Wi *et al*. (2012) for the winter season. For this case, we found that the impact of climate change would be to increase precipitation, stream discharge and reservoir levels in the SRB over both rainy seasons. While this contradicts studies in the southwest USA (Christensen and Lettenmaeir 2007, Seager *et al*. 2007), existing uncertainties surrounding climate change scenarios for the NAM region (Dominguez *et al*. 2010, Cavazos and Arriaga-Ramírez 2012, Cook and Seager 2013), especially in northwest Mexico, suggest that increase of precipitation is a plausible future outcome.

More importantly, the combination of the semi-distributed hydrological model and reservoir optimization algorithm lays the foundation for additional studies that reduce uncertainties related to model structure and parameter values and account for errors in precipitation forcing and stream discharge measurements, possibly using ensemble approaches (e.g. Mascaro *et al*. 2010, 2013). In addition, the combined tools used here can be readily transferred to water resources managers in the SRB since these are based on long-term ground observations and account for best-available information on the hydrological and reservoir systems. Furthermore, the results of this study should be informative to water resources stakeholders and decision-makers who require quantitative predictions of the potential impacts of climate change and its interaction with proposed infrastructure, possibly delivered through engagement processes such as participatory modelling (e.g. Robles-Morua *et al*. 2014).

Acknowledgements Arturo López Ibarra from CONAGUA provided valuable datasets on existing reservoir designs and historical storage and pool elevation records. We also thank contributions from Francina Dominguez and Erick Rivera-Fernández (University of Arizona) in the generation of the WRF products. We appreciate the efforts of two reviewers and the journal editor who provided useful comments that helped improve the quality of the manuscript.

Funding We acknowledge funding from the National Science Foundation (CBET-1014615) on the project: “Sustainable Water Resources for Communities under Climate Change: Can State-of-the-Art Forecasting Inform Decision-Making in Data Sparse Regions?”.

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APPENDIX

Nonlinear programming formulation

The following nonlinear program (NLP) model is developed for the reservoir operations under the objective:

$$\max Z = \sum_{t-1}^{T} R_t \tag{A1}$$

subject to the following constraints:
Mass balance:

$$\mathrm{ST}_{t+1} = \mathrm{ST}_t + Q_t - R_t + P_t - E_t \tag{A2}$$

Reservoir storage (level) range:

$$\mathrm{ST}_t \leq \mathrm{ST}_{\max} \tag{A3}$$

$$\mathrm{ST}_t \geq \mathrm{ST}_{\min} \tag{A4}$$

Reservoir stage–storage and stage–surface area relations:

$$\mathrm{ELE}_t = f(\mathrm{ST}_t) \tag{A5}$$

$$\mathrm{SA}_t = f(\mathrm{ELE}_t) \tag{A6}$$

Precipitation and evaporation:

$$P_t = (\text{Daily Rainfall Depth}) \times \mathrm{SA}_t \tag{A7}$$

$$E_t = (\text{Daily Evaporation Depth}) \times \mathrm{SA}_t \tag{A8}$$

Release rate:

$$R_t \leq R_{\max} \tag{A9}$$

where the variables are:

ST_t	Reservoir storage at time t
Q_t	Inflow to the reservoir at time t
P_t	Precipitation into reservoir surface at time t
E_t	Evaporation from reservoir surface at time t
ELE_t	Reservoir elevation at time t
SA_t	Reservoir surface area at time t
R_t	Daily (at time t) release from the reservoir
$\mathrm{ST}_{\max}$	Upper limit of the reservoir storage
$\mathrm{ST}_{\min}$	Lower limit of the reservoir storage
$R_{\max}$	Maximum allowable release
T	Total time period