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RESEARCH ARTICLE

# The ecohydrological vulnerability of a large inland delta to changing regional streamflows and upstream irrigation expansion

Elmira Hassanzadeh[1] | Amin Elshorbagy[1,2] | Ali Nazemi[1,3,4] | Timothy D. Jardine[1,4,5] | Howard Wheater[1,2,4] | Karl-Erich Lindenschmidt[1,4]

[1] Global Institute for Water Security, University of Saskatchewan, National Hydrology Research Centre, 11 Innovation Boulevard., Saskatoon, Saskatchewan S7N 3H5, Canada

[2] Department of Civil and Geological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan S7N 5A9, Canada

[3] Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve Boulevard West, Montreal, Quebec H3G 1M8, Canada

[4] School of Environment and Sustainability, University of Saskatchewan, Kirk Hall, 117 Science Place, Saskatoon, Saskatchewan S7N 5C8, Canada

[5] Toxicology Centre, University of Saskatchewan, 44 Campus Drive, Saskatoon, Saskatchewan S7N 5B3, Canada

**Correspondence**
Elmira Hassanzadeh, Global Institute for Water Security, University of Saskatchewan, National Hydrology Research Centre, 11 Innovation Blvd., Saskatoon, SK S7N 3H5 Canada.
Email: elmira.hassanzadeh@usask.ca

## Abstract

Future climate change and anthropogenic interventions can alter historical streamflow conditions and consequently degrade the health and biodiversity of freshwater ecosystems. Future ecohydrological threats, however, are difficult to quantify using the cascade of climate and hydrological models due to various uncertainties involved. This study instead uses a fully bottom-up approach to evaluate the ecohydrological vulnerability of the Saskatchewan River Delta (SRD), the largest inland delta in North America, to changing streamflow regime and irrigation expansion. An ensemble of perturbed streamflow sequences, along with scenarios of current and expanded irrigation, was generated and fed into a regional water resource system model. Results show that the streamflow regime in the delta is more sensitive to upstream changes in annual flow volume than peak flow timing and/or irrigation expansion. The sensitivity to changes in flow volume, however, may be intensified when combined with changes in peak timing. Shifts in the upstream peak flow timing can alter the magnitude and timing of peak flow to the delta, with prime importance to aquatic biota that are adapted to historical rhythmicity in peak flows and timing. Irrigation expansion decreases the magnitude and frequency of the peak flows, alters the frequency of average and low flows, and slightly shifts the timing of the mean annual peak flow in the SRD. This can lead to isolation of lakes and wetlands from the main stream. Our results highlight the ecohydrological vulnerability of the SRD under potential changing conditions and can assist in proposing adaptation policies to protect this ecosystem.

**KEYWORDS**

anthropogenic intervention, bottom-up impact assessment, ecohydrological vulnerability, Saskatchewan River Delta, streamflow alteration

## 1 | INTRODUCTION

Long-term streamflow characteristics, known as "natural streamflow regime", shape the structure and functioning of freshwater ecosystems (Poff & Zimmerman, 2010). Any deviation from natural streamflow regime, therefore, may adversely affect the ecosystem livelihood (IPCC, 2012). This so-called "vulnerability" can be due to the combination of multiple drivers (Gouldby & Samuels, 2005), which individually may or may not cause harm to the system (UNISDR, 2009). In this context, climate change and human activities are known as key drivers of the shift in streamflow regimes globally. On the one hand, a warming climate has altered key meteorological characteristics, such as regional and global temperature and precipitation, and has intensified the hydrological cycle across various scales (Nijssen, O'Donnell, Hamlet, & Lettenmaier, 2001; Oki & Kanae, 2006). This has resulted in significant changes in the natural characteristics of streamflow, including the magnitude, timing, and variability and frequency of high and low flows (Milly, Dunne, & Vecchia, 2005; Viviroli et al., 2011). On the other hand, increasing water resource management as well as changes in vegetation, land use, and land management can contribute to alterations in streamflow conditions (Ireson et al., 2015; Magilligan & Nislow, 2005; Nazemi, Wheater, Chun, Bonsal, & Mekonnen, 2016). The resulting changes in the flow regime can consequently change the distribution, abundance, and diversity of riparian and aquatic

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habitats, with potentially serious effects on aquatic resources on which humans and ecosystems depend (Matthews & Marsh-Matthews, 2003; Poff et al., 2010; Stromberg et al., 2007). These include some catastrophic cases such as Urmia Lake and the Aral Sea in western Asia (see AghaKouchak et al., 2015; Philip, 1988).

From a management perspective, it is crucial to explore the vulnerabilities in freshwater ecosystems to changing streamflow conditions (Adam, Hamlet, & Lettenmaier, 2009; Döll & Schmied, 2012; Wilby, 2016). This requires projecting the streamflow regime under a changing climate and anthropogenic interventions. The most common framework to estimate future streamflow is based on a cascade setting of different models and is called the "top-down" approach. In top-down assessments, streamflow series are obtained from hydrological models that are fed by downscaled meteorological variables obtained from Generalized Circulation Models (GCMs; see Wilby, 2005). Accordingly, by utilizing a set of ecohydrological indicators and/or ecological models, the effects of changing streamflow regimes on ecosystems are assessed (e.g., Fung et al., 2013; Mittal, Bhave, Mishra, & Singh, 2016; Mohammed, Bomblies, & Wemple, 2015).

Despite major developments, such analyses using GCM projections are still limited and include deep uncertainties. These uncertainties can be large and irreducible because they have limited ability to account for underlying physical processes at different spatial–temporal scales (Wilby, 2010). In addition, different climate models provide dissimilar climate projections, which often suggest a wide range of changes in streamflow regime (e.g., Zhang, Huang, Wang, & Zhang, 2011). Primarily, the sign and magnitude of future ecological changes depend on the selection of climate models (e.g., Fu, Pollino, Cuddy, & Andrews, 2015; Papadaki et al., 2016). Furthermore, different downscaling techniques, either statistical or dynamical, can result in significantly different projections at the scale of consideration (e.g., Fowler, Blenkinsop, & Tebaldi, 2007). Various studies have used Regional Climate Models, that is, dynamically downscaled GCMs, to produce more realistic and higher resolution climate outputs (e.g., Rahman et al., 2015). However, the results of Regional Climate Models are also uncertain, mainly due to variability in internal parameterization, mathematical formulation, and boundary forcing, depending on the choice of GCMs (Fowler et al., 2007). Moreover, regardless of how good downscaled climate projections are, hydrological models are still required to convert these realized climate futures into estimated water availability conditions. However, hydrological models include a great deal of uncertainty, mainly due to process simplifications and the lack of identifiable parameterizations (Beven, 2006). These uncertainties are large and can inevitably propagate into impact assessments and may mislead in the identification of potential ecological vulnerabilities in the future (Arnell & Gosling, 2013; Kundzewicz et al., 2008; Wilby & Dessai, 2010).

In response to these challenges, various studies have recommended the use of stress tests to assess the sensitivity of water resource systems to a wide range of plausible climate conditions without direct use of downscaled GCM projections (e.g., Ben-Haim, 2006; Brown, Ghile, Laverty, & Li, 2012; Kasprzyk, Nataraj, Reed, & Lempert, 2013; Lempert, Groves, Popper, & Bankes, 2006; Prudhomme, Wilby, Crooks, Kay, & Reynard, 2010). In such stress tests, GCM projections introduce a plausible range of change in climate conditions, which is then used in weather generators to synthesize multiple climate realizations under future conditions. This provides a "bottom-up" basis with which overall system vulnerabilities under likely future conditions can be quantified without being limited to only climate model outputs. Due to this capability, the results of ensuing vulnerability assessments are not outdated when new climate projections become available (Herman, Reed, Zeff, & Characklis, 2015; Steinschneider et al., 2015). In addition, the detection of system performance under a range of possible conditions can allow identification of critical thresholds, beyond which the system becomes vulnerable. Under such conditions, policy adjustments should be made to reduce the risk of associated system failure (Brown & Wilby, 2012). Due to these advantages, there is an emerging literature on using the bottom-up framework for water resource management and adaptation under climate change (e.g., Matrosov, Woods, & Harou, 2013; Whateley, Steinschneider, & Brown, 2016). In the context of ecohydrological vulnerability assessment, Singh, Wagener, Crane, Mann, and Ning (2014) applied this framework to explore changes in streamflow indices under climate and land use change. Using this framework, Poff et al. (2015) identified vulnerability thresholds and explored which adaptation actions should be taken and when they should be taken, to avoid failure under a wide range of climate conditions.

Despite some advantages, bottom-up vulnerability assessments still require hydrological models to map from the model-independent climate futures to future streamflow conditions, and hence include substantial uncertainty (Nazemi & Wheater, 2014a). In fact, various studies have argued that uncertainties in the hydrological model structures and/or parameters may be equal to or greater than those associated with climate models (Steinschneider, Wi, & Brown, 2014; Wilby & Harris, 2006) and can add large uncertainty to the vulnerability assessment. Moreover, hydrological models are still limited in representing changes in streamflow conditions as a result of human interventions such as water withdrawal and reservoir regulations (Nazemi & Wheater, 2015a, 2015b). To overcome this, some "fully bottom-up" schemes have been proposed to stochastically generate streamflow sequences without incorporating any hydrological and/or climate models (see Borgomeo, Farmer, & Hall, 2015; Nazemi, Wheater, Chun, & Elshorbagy, 2013). In these schemes, consistent with model-based projections and/or operational constraints, the historical streamflow regime is perturbed with respect to changes in the key annual streamflow characteristics. As fully-bottom up approaches can accommodate the combined effects of multiple drivers using a wide range of perturbed streamflow realizations, they become quite useful when alterations in streamflow conditions are caused by both climatic and anthropogenic drivers.

There are various freshwater ecosystems throughout the world in which ecohydrological alterations can be caused by both climate change and human interventions (e.g., Sala et al., 2000). One important regional example of such an ecosystem is the Saskatchewan River Delta (SRD), in western Canada. The SRD is the largest inland delta in North America (MacKinnon, Sagin, Baulch, Lindenschmidt, & Jardine, 2015) and is among the richest regions for wildlife abundance and diversity in Canada and globally (Partners for Saskatchewan River Basin, 2009). The SRD is located at the Saskatchewan and Manitoba

provincial boundary, which is downstream of the complex water resource system of the Canadian Prairies and the terminus of the South and North Saskatchewan Rivers (SSR and NSR, respectively), the Saskatchewan River (SR) system. These rivers initiate in the Canadian Rockies in western Alberta. As they flow downstream, the SSR and NSR supply various human demands in Alberta and then Saskatchewan before reaching the delta. Regional streamflow flow modeling is extremely challenging due to complex prairie runoff generation mechanisms (Mekonnen, Nazemi, Mazurek, Elshorbagy, & Putz, 2015) as well as significant human interventions (Wheater and Gober, 2013). A warming climate and extensive water resource management in Alberta have already altered the characteristics of the inflowing SSR to Saskatchewan (Martz, Bruneau, & Rolfe, 2007; St Jacques, Sauchyn, & Zhao, 2010). These changes are likely to increase in the future due to further impacts of climate change on mountainous headwaters and growing socio-economic activities throughout the province (Pomeroy, Fang, & Williams, 2009; Schindler & Donahue, 2006). In addition, Saskatchewan is exploring expansion of irrigation to address global food security and stimulate provincial economic development (Saskatchewan Ministry of Agriculture, 2012). The combined effects of these changes may considerably alter the ecohydrological characteristics of the SRD, which is downstream of these sources of change.

The aim of this study is to evaluate potential changes in the ecohydrological characteristics of the SRD as a result of changes in streamflow entering Saskatchewan and irrigation expansion within the province. To do this, a wide range of modified streamflow series at the Alberta/Saskatchewan (AB/SK) boundary were generated stochastically using the reconstruction approach proposed by Nazemi et al. (2013). The ensemble of flow sequences combined with the current and increased irrigation areas were fed into a water resources model developed for Saskatchewan (Hassanzadeh, Elshorbagy, Wheater, & Gober, 2014) to simulate the streamflow regime in the SRD under a wide envelope of changing conditions. Accordingly, using a set of indicators, the ecohydrological vulnerability of the SRD to changing conditions was evaluated. The characteristics of the SRD and the upstream water resource system are first discussed in more detail, followed by a description of the streamflow reconstruction procedure, water resource system modeling, and ecohydrological impact assessment. Then, the effect of changing conditions on the ecohydrological indicators of the SRD are presented and discussed. Finally, the key findings, along with limitations and suggestions for future works are elucidated.

## 2 | CASE STUDY

The SRD covers approximately 10,000 km$^2$ and contains a complex network of abandoned and active river channels, marshy shallow lakes, and wetlands (Smith, Morozova, & Gibling, 2014)—see Figure 1. This highly productive ecosystem has a diverse vegetation coverage and is

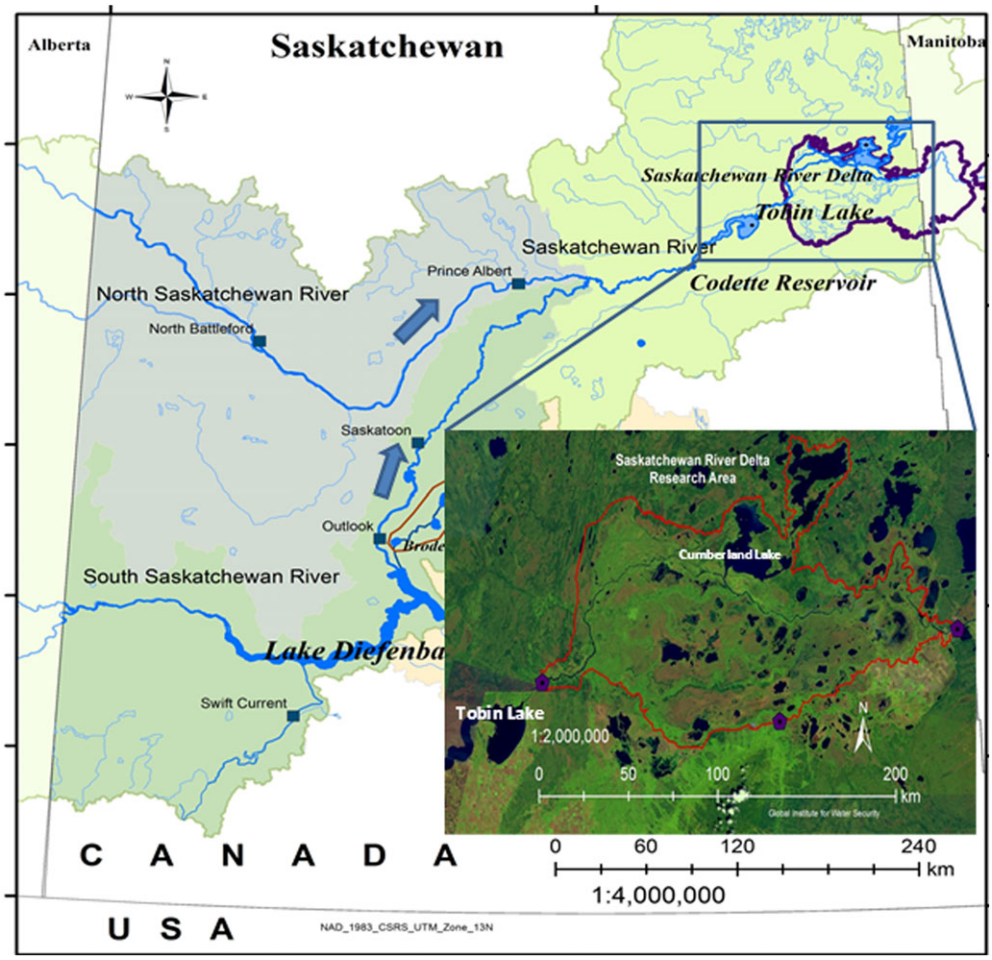


**FIGURE 1** The water resource system in Saskatchewan and the Saskatchewan River Delta at the Saskatchewan/Manitoba boundary

home to a variety of native and migrating species, particularly birds, for which the SRD has been recognized as a "globally significant Canadian Important Bird Area" (Schmutz, 2001). The SRD is also home to First Nations and Métis people whose livelihoods depend on fishing, hunting, and trapping in the delta (Abu, Reed, & Jardine, 2016). As a result, change in the ecohydrological characteristics of the delta can have high socioeconomic and cultural consequences for these communities (Partners for Saskatchewan River Basin, 2009).

Almost 80% of the flow to the delta is derived from the NSR and SSR (Smith et al., 2014), which together have a long-term annual discharge of 421 $m^3/s$ below Tobin Lake just upstream of the delta (data from 1980 to 2010 at Water Survey of Canada gauge 05KD003). NSR and SSR flows originate from the Canadian Rockies and reach Saskatchewan with long-term annual discharges of 217 and 207 $m^3/s$, respectively, during the same period (Water Survey of Canada gauges 05GG001 and 05HG001). This flow is highly regulated, particularly in the southern tributary. The multipurpose Lake Diefenbaker reservoir (built in 1967 with a volume of about 9400 million $m^3$) is one of the largest reservoirs in the world and is the main flood defense and water supply infrastructure in the province (Pomeroy, De Boer, & Martz, 2005). The operation of Lake Diefenbaker has completely altered the natural SSR flow hydrograph, with substantially higher winter flows and lower spring freshets (Pomeroy & Shook, 2012).

After release from Lake Diefenbaker's Coteau Creek hydropower plant, the regulated SSR passes Saskatoon, the largest city in the province, and meets the NSR, approximately 40 km east of Prince Albert, to form the SR (Figure 1). Further downstream, Codette and Tobin lakes were constructed on the SR in 1986 and 1963, with volumes of 400 and 2200 million $m^3$, to support the 255 MW Nipawin and the 288 MW E.B. Campbell hydropower stations, respectively. Although these two reservoirs do not have the same regulating effect as Lake Diefenbaker, they have considerably changed the natural sediment transport patterns in the SR (Ashmore & Day, 1988) and have altered the natural ecosystem of the delta as barriers to migration of aquatic species and by disrupting riparian habitat (Partners for Saskatchewan River Basin, 2009).

Apart from historical changes, the SRD faces two major future challenges. First, additional changes in the upstream inflow regime are expected both due to climate change (e.g., Martz et al., 2007; Sauchyn et al., 2009) and potential management interventions in the upstream province of Alberta (Gober & Wheater, 2014). Various studies have found that the warming climate has already changed the snow-to-rain ratio and snow and glacial melt, as well as the characteristics of regional rainfall (Chun, Wheater, Nazemi, & Khaliq, 2013; Harder, Pomeroy, & Westbrook, 2015; Shook & Pomeroy, 2012). These effects will continue in the future and will ultimately impact the long-term annual volume and peak timing of the SSR and NSR flows (e.g., Lapp, Sauchyn, & Toth, 2009; Shepherd, Gill, & Rood, 2010). This is in agreement with projections obtained using climate and hydrological models. For instance, using various GCMs and by forcing a hydrological model, the North Saskatchewan Watershed Alliance (2008) found that the changes in the long-term annual NSR flow volume may range from −23% to 15% in the future. Similarly, Pomeroy et al. (2009) projected a range of changes in the long-term annual SSR flow volume at the AB/SK boundary, from −22% to 8%. These projections, however, are unable to account for the complex water resource management schemes planned in Alberta.

Secondly, in addition to changes in the incoming streamflows, total irrigation water demand in Saskatchewan is expected to considerably increase in the future. The current irrigation area in Saskatchewan, which is fed by Lake Diefenbaker, is about 243 $km^2$ (SWSA, 2016). This area, however, might reach 2266 $km^2$ in the future (Saskatchewan Ministry of Agriculture, 2012). All of these changes have the potential to impact the ecohydrological characteristics of the SRD.

## 3 | METHODS AND MATERIALS

### 3.1 | Stochastic reconstruction of changing streamflow regime

The streamflow reconstruction algorithm proposed by Nazemi et al. (2013) generates synthetic weekly streamflow sequences, corresponding to predefined changes in the long-term annual flow volume and peak timing. This algorithm has been frequently used for generating synthetic streamflow series in the Canadian Prairies (Hassanzadeh, Elshorbagy, Wheater, & Gober, 2016; Hassanzadeh, Elshorbagy, Wheater, Gober, & Nazemi, 2015; Nazemi & Wheater, 2014b; Nazemi et al., 2013). In brief, the algorithm requires observed weekly flow series as well as hypothetical changes in the long-term annual flow volume and peak timing. These changes are incorporated into observed streamflow through additive and/or multiplicative change factors that are applied to the statistical distributions of annual flow volume and timing of the peak flow using quantile mapping (Panofsky & Brier, 1968). These modifications form new streamflow distributions, from which perturbed streamflow realizations with embedded changes can be stochastically generated. To do so, the joint empirical distributions within the perturbed weekly streamflow time series are represented using copula methodology (Nazemi & Elshorbagy, 2012), which enables maintenance of the temporal dependence structure within the stochastically generated streamflow series.

This method was used to construct the ensembles of possible SSR and NSR flow sequences at the AB/SK boundary to evaluate the effect of changing upstream flow conditions on the SRD. For this purpose, the sampling domain suggested by Hassanzadeh et al. (2015, 2016) was selected based on the cumulative effects that can potentially cause changes in the streamflow conditions due to changing climate and water management, as well as land use and land management (see e.g., Martz et al., 2007; Pomeroy et al., 2009). These include −5 to 8 weeks change in long-term annual peak flow timing and −25% to 25% change in long-term annual flow volume, where the historical period covers weekly NSR and SSR flows from 1980 to 2010. Considering 1 week and 5% increments in the long-term annual timing of the peak and flow volume, respectively, 154 streamflow scenarios (14 shifts in annual peak [−5, −4 … +4, +8] × 11 changes in annual flow volume [−25%, −20% … +20%, +25%]) were considered for stochastic sampling. For each of the changing streamflow scenarios, 100 realizations were generated for both SSR and NSR flows, each with a 31 year length, similar to the considered historical period. In contrast to Hassanzadeh et al. (2015), the NSR and SSR flows were generated

independently, without considering their spatial dependency, as current regression-based methods for handling the spatial dependency can significantly under-represent high flow quantiles. Further analysis showed that independent sampling can, conversely, capture the full range of observed extremes. The independently generated realizations for the NSR and SSR flows, using the same factors of change in annual volume and timing of the peak, were randomly paired to represent a uniform change in incoming flow to Saskatchewan.

In total, 15,400 time series (154 × 100) with a length of 31 years were generated for the NSR and SSR flows at the AB/SK boundary. For the sake of notation, here the (x,y) pair defines a cell, which describes a specific scenario of long-term changes in the timing of the long-term annual peak (x; in weeks) and relative change in long-term annual flow volume (y; in %). 100 streamflow realizations with the same length were generated for each cell that represents different time series with identical x and y. For instance, 100 streamflow realizations with 4 weeks earlier annual peak flow timing and 25% increase in annual flow volume can be labeled as (−4,25%). The potential changes in the ecohydrological indicators were evaluated for all 154 cells; however, nine cells, that is, (−4,25%), (−4,−25%), (4,25%), (4,−25%), (0,0), (0,25%), (0,−25%), (4,0), and (−4,0) were selected for detailed discussion in Section 4. Among these, eight cells represent the boundary conditions of the whole domain of change and cell (0,0) represents a no-change scenario and includes the historical streamflow series.

Figure 2 illustrates the ensemble of long-term annual hydrographs under the entire range of change and expected (averaged over 100 realizations) long-term annual hydrographs under the nine selected scenarios of change. The analyses of the reconstructed streamflow series revealed that the algorithm could successfully maintain the prespecified change in the long-term annual flow volume and peak timing. Further validation of the stochastic streamflow reconstruction method is provided in Nazemi et al. (2013) and Hassanzadeh et al. (2015).

## 3.2 | Water resource system model

The Sustainability-oriented Water Allocation, Management, and Planning model ($SWAMP_{SK}$; Hassanzadeh et al., 2014) was used to simulate the water resource system in Saskatchewan. $SWAMP_{SK}$ was developed using the system dynamics approach (Forrester, 1961), which has been widely used for modeling water resource systems (e.g., Hassanzadeh, Zarghami, & Hassanzadeh, 2012; Mirchi, Madani, Watkins, & Ahmad, 2012; Sahin, Siems, Stewart, & Porter, 2016; Simonovic, 2009). $SWAMP_{SK}$ has a weekly temporal resolution and was developed based on the operational characteristics of the system during the historical period, extending from1980 to 2010. The model considers abstraction from reservoirs that allocate water to competing water demands including municipal, industrial, environmental, irrigated agricultural, and hydropower demands. The allocation considers the antecedent reservoir storage, current water availability and demand,

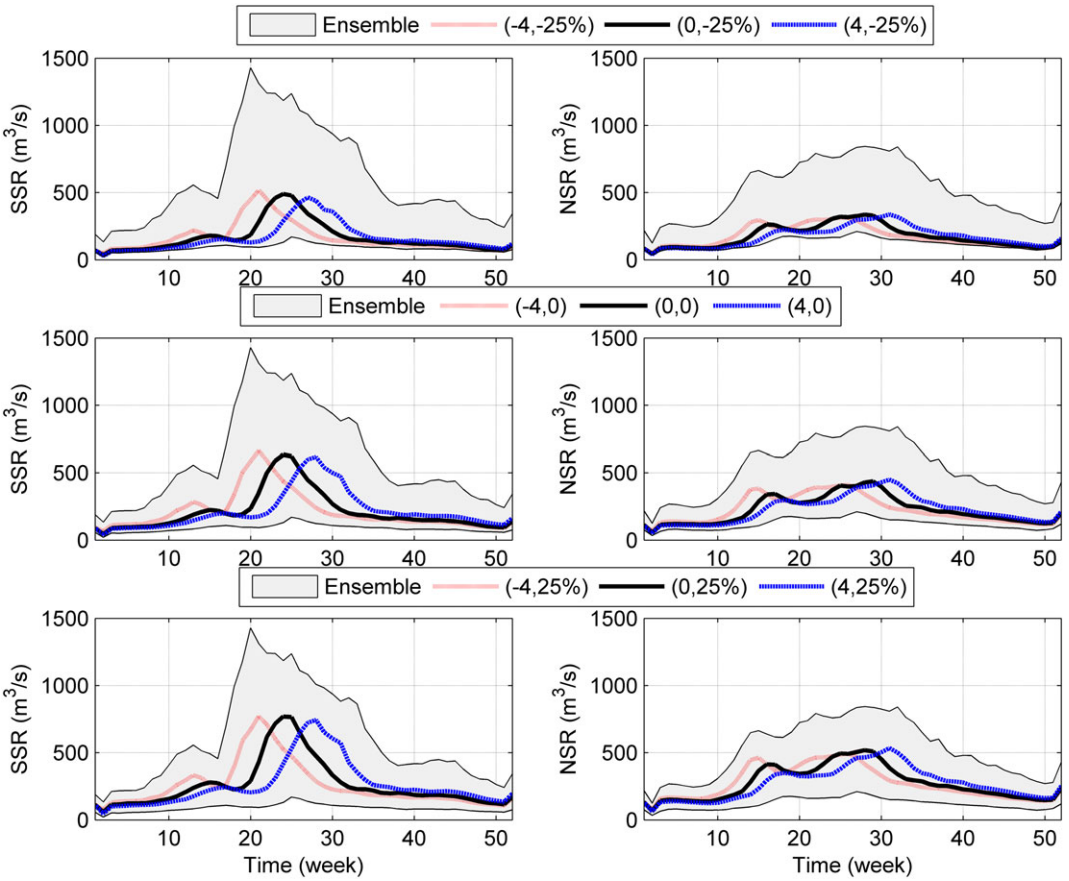


**FIGURE 2** An ensemble of long-term annual hydrographs under the entire range of change (shaded area), and expected long-term annual hydrograph under the nine selected scenarios of change in streamflow characteristics (line) for the South (left) and North Saskatchewan (right) rivers at the Alberta/Saskatchewan boundary. NSR = North Saskatchewan Rivers; SSR = South Saskatchewan Rivers

operational rule curves, as well as water allocation priorities, and requires a minimum storage to be maintained in the reservoirs. Rule curves dictate the minimum, maximum, and ideal storage levels in the reservoir. The minimum and maximum storage levels for Lake Diefenbaker are, respectively, 552.7 m and 556.8 m and for Tobin Lake are 311.5 m and 313.64 m. The ideal rule curve is time dependent and presents the optimal storage level. Water allocation priorities formulate the relative importance of various demand sectors, which decrease from municipal to industrial, environmental, irrigated agricultural, and hydropower sectors. Among various water demands, municipal and industrial water demands are licensed demands. Environmental demand is the minimum downstream flow requirement equal to 42.5 $m^3/s$ from Lake Diefenbaker and 150 $m^3/s$ from Tobin Lake (SWSA, 2012). The irrigation water demand is calculated based on irrigation efficiency, crop area, and crop irrigation demand, which is estimated dynamically for the main crops in Saskatchewan during the growing season as a function of climate variables, soil moisture content and allocated crop water. Hydropower demand is calculated based on the rated head, power capacity, turbine and generator efficiencies, difference between headwater and tail water elevations, and head loss. Hydropower allocation has been considered in conjunction with reservoir storage and scheduled to keep the water level close to the ideal storage level. Such water allocation policies are implemented in the model by "if-then" rule functions. The $SWAMP_{SK}$ model output includes the reservoir levels and storage, allocated water to various sectors and river flows including the incoming flow to the SRD.

Since Lake Diefenbaker and Tobin Lake play key roles in regulating the incoming flow to the delta due to storage and release processes, we recalibrated the parameters of their hydropower releases to improve the accuracy of flow entering the SRD. Considering the water balance equation, the reservoir storage dynamics can be described as:

$$S(t_n) = \int_{t_0}^{t_n} [F(t) + P(t) - E(t) - SP(t) - RE(t) - (aRG(t) + b)]dt + S(t_0), \quad (1)$$

where *S*, *F*, *P*, *E*, and *SP* are storage, inflow, precipitation, evaporation, and spillage, respectively, and *t* is time (weeks) between $t_0$ and $t_n$ ($t_0 \le t \le t_n$). *RE* is total withdrawal for a set of water demands (e.g., municipal, industrial, environmental, and irrigation water demand) excluding hydropower, and *RG* is water withdrawal for the hydropower sector. The calibration parameters are slope *a* and intercept *b* that correct the initial hydropower release based on the observed flow downstream of the reservoir. The Powell hill climbing optimization technique (Powell, 1964), embedded in the Vensim DSS (Ventana Systems, 2003), was used to find the optimum values for four parameters $a_D$ and $b_D$, as well as $a_T$ and $b_T$ for Lake Diefenbaker and Tobin Lake, respectively, in such a way that the sum of the squared difference between the simulated and observed flows entering the SRD is minimized. The calibration and validation periods include 67% and 33% of the data during 1980 to 2010, respectively. The calibrated values for $a_D$, $b_D$, $a_T$, and $b_T$ were 0.5, 49 $m^3/s$, 0.82, and 165 $m^3/s$, respectively. The statistical performance measures (i.e., $R^2$, Root Mean Squared Error, and Mean Absolute Relative Error) were used to compare $SWAMP_{SK}$ performance before and after calibration in simulating the observed flow entering the SRD (Table 1). Comparison between top and bottom rows show that calibration improved $SWAMP_{SK}$ model performance and that the calibrated model can sufficiently describe the observed flow to the delta.

All 477,400 (15,400 × 31) annual weekly flow hydrographs for each tributary were input to the recalibrated $SWAMP_{SK}$. The water resource system was simulated twice, considering the current level of irrigation and a 10-fold increase in irrigation area. Using this simulation scheme, a wide range of incoming flows to the delta can be obtained to jointly represent the effects of the changing inflow regime and irrigation expansion.

## 3.3 | Quantifying ecohydrological change

Although the exact impact of the changing flow regime on the ecosystem of the SRD is not well understood (Wheater & Gober, 2015), it is obvious that changes in streamflow regime to the SRD perturb the natural connectivity between lakes and wetlands in the delta. This can affect the integrity of the freshwater ecosystem including limiting access to spawning and nursery areas for fishes, reducing riparian habitat and dampening sediment transport and deposition.

Earlier classifications of streamflows and wetland connectivity were used to estimate ecohydrologically relevant flow metrics for the SRD. Sagin, Sizo, Wheater, Jardine, and Lindenschmidt (2015) developed a mathematical relationship between the SR flow discharge ($m^3/s$) and estimated Surface Water Coverage Area (SWCA, $km^2$). This relationship, that is, $SWCA = 1.76 \times SR^{0.63}$, was obtained based on a set of remote sensing products during multiple ice-free seasons. Using this relationship, MacKinnon et al. (2015) classified wetland connectivity in the delta during different incoming flows from the SR. They identified five specific flow categories, namely drought (i.e., < 350 $m^3/s$), low flood (i.e., 350 $m^3/s \le$ and <500 $m^3/s$), moderate flood (i.e., 500 $m^3/s \le$ and <1000 $m^3/s$), high flood (i.e., 1000 $m^3/s \le$ and <2000 $m^3/s$), and extreme flood (i.e., ≥ 2000 $m^3/s$) conditions. They found, using winter field surveys, that SRD lakes and wetlands with reduced connectivity have lower water quality than those that are more connected. In particular, less-connected lakes had lower dissolved oxygen and higher ammonium concentrations than those that maintained connection to the main channel year-round. Abu et al. (2016) expanded on these observations by combining archival and instrumental data with interviews with land users to show that reduced flows lead to vegetation

**TABLE 1** The $SWAMP_{SK}$ statistical performances compared to observed flow entering the delta for the entire simulation period before utilizing calibration, as well as for calibration and validation datasets, respectively

| Description/Performance | | RMSE ($m^3/s$) | MARE | R |
|---|---|---|---|---|
| $SWAMP_{SK}$ performance before calibration | Simulation period | 153 | 0.29 | 0.81 |
| $SWAMP_{SK}$ performance after 4-parameter calibration | Calibration | 134 | 0.23 | 0.83 |
| | Validation | 140 | 0.24 | 0.86 |

*Note.* $SWAMP_{SK}$ = Sustainability-oriented Water Allocation, Management, and Planning model.

encroachment, reduced water quality in wetlands, fewer fur-bearing mammals and declines in certain fish species, namely goldeye (*Hiodon alosoides*) and lake sturgeon (*Acipenser fulvescens*). Both of these fish species have lost spawning habitat as a result of lower flows.

Here, a total of eight indicators were used to evaluate the potential changes in the SRD's hydrologic regime and ecosystem health as a result of changing upstream flows and irrigation expansion (see Table 2).

Each of these indicators represents a particular aspect of the streamflow regime that is relatively independent of the others. In brief, Indicator 1 elucidates how changes in the magnitude of the long-term annual low flow can affect ecosystem conditions including temperature and oxygen concentrations, connectivity among river reaches in intermittent rivers, and water quality. Change in the magnitude of the long-term and extreme peak flows, Indicators 2 and 3, can considerably affect the revival of the delta, in particular riparian and wetland vegetation recruitment, sediment,and nutrient deposition (Smith & Pérez-Arlucea, 2008), and channel formation. Change in Indicator 4, that is, timing of the long-term annual peak flow, can affect phenology of vegetation, spawning cues and reproduction of fishes, and nesting success of waterfowl. Indicators 1 to 4 have been widely used in the literature to assess the effects of climate change on freshwater ecosystems (e.g., Döll & Zhang, 2010; Gibson, Meyer, Poff, Hay, & Georgakakos, 2005; Poff & Zimmerman, 2010). However, these indicators alone might not be able to fully capture the characteristics of the ecosystems in river deltas. For instance, recent research on tropical floodplain rivers shows that ecosystem biodiversity and productivity are maximized when peak flow timing and magnitude are predictable over years, that is, floods are rhythmic (Jardine et al., 2015). Therefore, in addition to Indicators 1 to 4, Indicators 5 and 6 were used in this study to measure the predictability in magnitude and timing of the annual peak flow in the SRD. This predictability can be assessed using standard statistics—here Coefficient of Variation for both peak flow magnitude and timing was used.

Apart from the generic indicators noted above, Indicators 7 and 8 are specific to the SRD and represent floodplain inundation, connectivity, and the limnological conditions of lakes and wetlands in this area. In brief, Indicator 7 estimates the frequency of flow under five specific streamflow categories, characterizing different levels of connectivity among lakes and wetlands in the SRD, from widely isolated (i.e. flows less than 350 $m^3/s$) to wholly connected lakes (i.e. flows higher than 2,000 $m^3/s$). Change in the levels of connectivity can affect the lake water quality dynamics and water chemistry, including the concentration of phosphorous, nitrogen, and dissolved oxygen (MacKinnon et al., 2015). This, accordingly, can affect both aquatic and riparian habitat conditions and can alter abundance or extirpation of species tolerant and intolerant to changes in water quality. Indicator 8 was used to describe the effect of upstream changes on the long-term SWCA in the delta in a typical ice-free season. Major change in this indicator influences fish distribution among habitats, regeneration of vegetation, and fur-bearing mammal production. Using historical SR flow data, Sagin et al. (2015) showed that peak summer SWCA has already decreased by ~50% over the last century owing to changes in upstream water resource conditions.

## 4 | RESULTS AND DISCUSSION

### 4.1 | Effects on the long-term annual low flow to the delta

To explore the changes in the long-term annual low flows entering the delta (Indicator 1 in Table 2), observed annual Q90 was averaged over 31 years and was compared with corresponding values under changing upstream streamflow with and without irrigation expansion. Figure 3 illustrates the relative change in the long-term annual Q90 for the nine selected scenarios of change in streamflow conditions, introduced in Section 3.1, under current (top panel) and expanded irrigation (bottom panel). These boxplots were obtained using 100 streamflow realizations for each set of streamflow conditions. Considering the boxplots from left to right, the long-term annual Q90 is more sensitive to changes in upstream annual flow volume than changes in annual peak flow timing. Intuitively, long-term annual low flows to the delta decrease when upstream flow volume decreases. In addition, long-term annual Q90 gradually increases when the upstream annual peak shifts to later dates under both current and increased irrigation areas. Interestingly, upstream flows with four weeks earlier annual peak timing and no change in annual volume, that is (−4,0), decrease long-term annual Q90 in the delta by 8% on average.

**TABLE 2** Indicators used to explore the effects of changing upstream streamflow conditions and irrigation expansion on the incoming flow to the delta

| Indicator | Delta characteristics | Observed values (1980–2010) |
|---|---|---|
| 1 | Long-term annual low flow | 247 $m^3/s$ |
| 2 | Long-term annual peak flow | 1051 $m^3/s$ |
| 3 | Extreme annual peak flow | 2531 $m^3/s$/week |
| 4 | Long-term timing of the annual peak flow | week 23 |
| 5 | Variability in annual peak flow magnitude over 31 years | CVmax =0.47 |
| 6 | Variability in annual peak flow timing over 31 years | CVmax =0.3 |
| 7 | The segmental streamflow frequency | 44.11% for drought<br>32.01% for low flood<br>21.09% for moderate flood<br>2.74% for high flood<br>0.06% for extreme flood |
| 8 | Long-term SWCA during ice-free season | 77 $km^2$ |

*Note*. CVmax = Coefficient of Variation; SWCA = Surface Water Coverage Area.

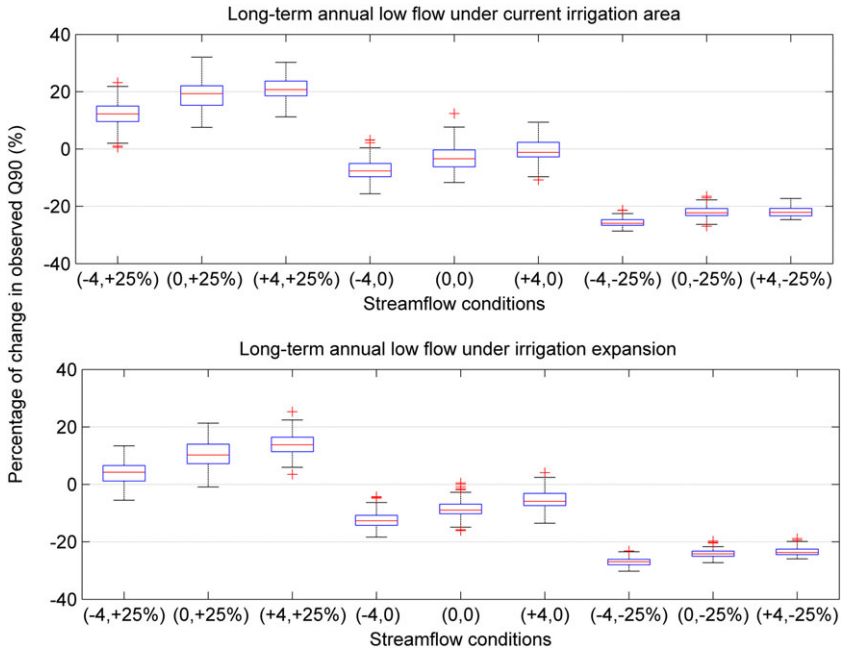


**FIGURE 3** Relative change (%) in the long-term annual low flow (Q90) to the delta for the nine selected scenarios of change in streamflow conditions under current (top row) and expanded (bottom row) irrigation. Each box represents the variations of relative change in the long-term annual Q90 over 100 realizations

Comparison between upper and lower panels reveals that the impact of irrigation expansion on the long-term annual Q90 is smaller than changes in upstream flow conditions. This may be due to the fact that low flows occur mostly in winter when no water is used for irrigation. The difference between the expected values of corresponding boxplots in the upper and lower panels revealed that the expected reductions in the long-term annual Q90 due to irrigation expansion are 8%, 5%, and 2% under high, historical, and low annual upstream flow volumes, respectively. This means that the relative impact of irrigation expansion on the long-term annual low flow is greater under higher upstream flow volume. This is rather intuitive, as Saskatchewan is required to maintain the licensed minimum flow below Tobin Lake. However, during higher flow conditions, there is no explicit policy constraint in place to ensure that the SRD benefits from increased annual volume, which is mainly consumed by irrigation. Any decrement in the long-term annual Q90, however, may have limited effects on the biology of the delta because it occurs during winter when low flows were the norm in the pre-dam era (Smith, Morozova, Perez-Arlucea, & Gibling, 2016, Wheater & Gober, 2015, Figure 2) and most plant and animal life is in a dormant state.

## 4.2 | Effects on the long-term annual peak flow to the delta

Figure 4 depicts the long-term annual peak flow to the delta under each of the changing conditions. For each realization in each cell, the

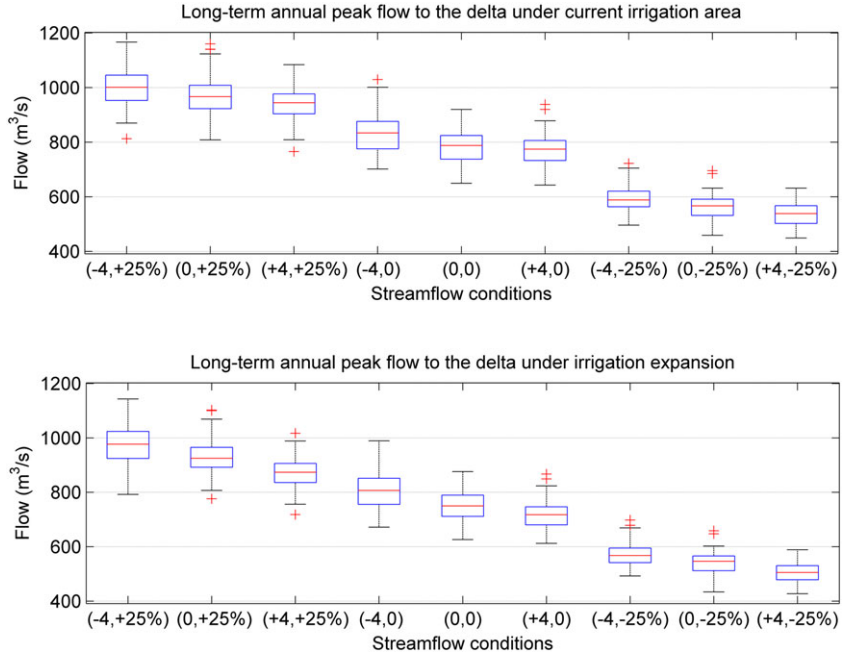


**FIGURE 4** Long-term annual peak of the streamflow to the delta for the nine selected scenarios of change in streamflow conditions under current (top row) and expanded (bottom row) irrigation. Each box represents the variations of long-term peak flow over 100 realizations

maximum weekly flow in a given year was identified and averaged over 31 years. Similar to the case of Q90, the long-term annual peak flow entering the delta is more sensitive to change in upstream annual flow volume than peak timing and/or irrigation expansion. Moreover, the long-term annual peak flow to the delta is sensitive to changes in the upstream annual peak flow timing, particularly when irrigation area is increased. In addition, long-term annual peak flow in the SRD decreases when the upstream annual peak flow shifts to later dates. Considering the effect of a warming climate, which includes an earlier melting and growing season, earlier peak timing is more likely to be the case for the SRD and may explain recent large peak flows in 2005 and 2011 that occurred in early June on the SSR (Shook & Pomeroy, 2016). As far as irrigation expansion is concerned, the expected rates of reduction in the long-term annual peak flow to the delta are 44 $m^3/s$, 38 $m^3/s$, and 24 $m^3/s$ under high, historical, and low upstream annual flow volume, respectively, which remain less than 4% of the observed long-term annual peak flow entering the delta. A decrease in the long-term annual peak flow can severely perturb natural sediment transport to the delta, which can adversely affect the SRD's replenishment. In particular, lower annual peak flows can lessen the level of connectivity and nutrient transport among the wetlands, lakes, and main channel (MacKinnon et al., 2015). It can lead to reduced recruitment of important riparian vegetation such as cottonwood trees, which require frequent riparian flooding to sustain new growth (Partners for the Saskatchewan River Basin, 2009). It also would reduce the renewal of water in peripheral wetlands that is needed to stimulate vegetation regrowth for production of waterfowl and fur-bearing mammals (Abu et al., 2016).

## 4.3 | Effects on the extreme annual peak flow magnitude to the delta

From the ecosystem perspective, extreme peak flows are critical in forming channels because sediments are flushed from the channel bed and deposited further downstream (Smith et al., 2016). In the case of the SRD, the annual peak flow to the delta is formed by the overlap of the flood hydrographs in the SSR and NSR, even though the exact timing of the incoming annual peaks to the province rarely coincides. In order to address the relationship between the extreme annual peak flows in the delta to the corresponding ones in the SSR and NSR, the extreme annual peak flow in the delta, $P_{i,j^*}$, was first found for each realization $i$ as the maximum of annual peak flows $P_{i,j}$ over $j = 1, \ldots, 31$ simulation years – $P_{i,j^*} = \max(P_{i,j})$. For the same year $j^*$, when $P_{i,j^*}$ occurred, annual peak flows in the SSR, $S_{i,j^*}$, and NSR, $N_{i,j^*}$, were identified. The summation of peaks at the boundary was then used to scale the extreme annual peak in the delta. This ratio $R_i$ indicates how much of the maximum possible peak flow (i.e., when both upstream peaks coincide) reaches the delta under each realization:

$$R_i = \frac{P_{i,j^*}}{S_{i,j^*} + N_{i,j^*}}. \quad (2)$$

Figure 5 shows the results of this analysis for nine selected streamflow conditions with current (top row) and expanded irrigation (bottom row).

The figure shows that the impact of water resource management on the formation of extreme peak flow magnitude in the delta depends on the upstream annual flow volume and peak timing. Most importantly, under high upstream flow volume, the extreme peak flow in the delta is less or equal to 80% of the sum of the upstream annual peak flows. This is due to the strict flood control policy in the operation of reservoirs, which forces a gradual release of large upstream peak flows. The variability in this ratio, however, is much larger under low upstream flow volume. This variability mainly depends on the antecedent water storage in the reservoirs and water demands in the region. Considering a specific annual flow volume, it is also noted that there is a greater chance of having larger extreme peak flows in the delta

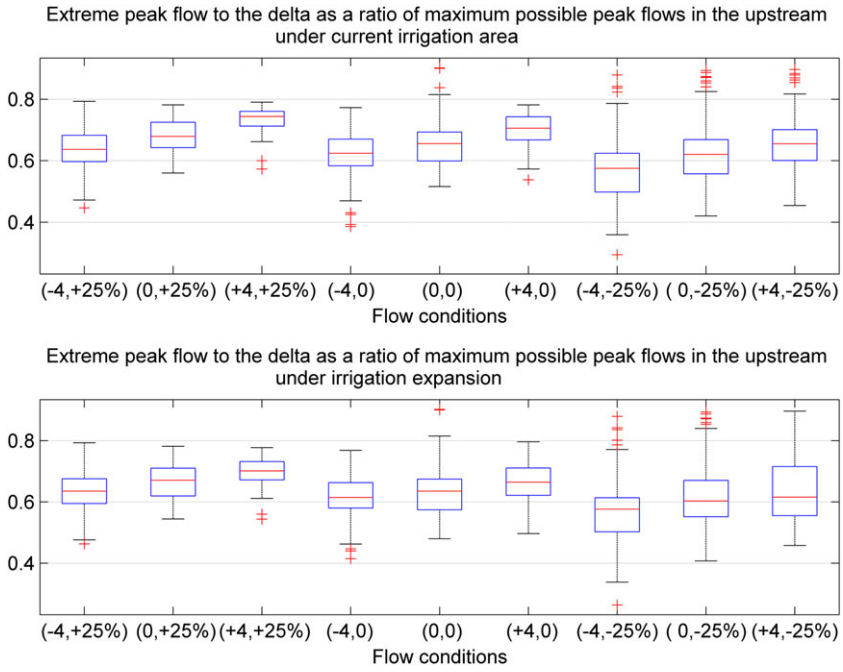


**FIGURE 5** Extreme peak flow to the delta as a ratio of maximum possible peak flows in the upstream. The maximum possible peak flows in the upstream is identified by the summation of peak flows in the SSR and NSR for the nine selected scenarios for streamflow conditions under current (top row) and expanded irrigation (bottom row). Each box represents the variations of relative change in extreme peak flow over 100 realizations. NSR = North Saskatchewan Rivers; SSR = South Saskatchewan Rivers

under the delayed timing of the upstream annual peak flow, while the variability in extreme annual peak is consistently larger under the earlier upstream peak flow timing. Additional analyses revealed that under the delayed upstream annual peak flow timing, the reservoirs are expected to have more antecedent storage. Therefore, when the peak flow arrives, they release more water downstream to accommodate the annual incoming peak from Alberta. This is not the case for an earlier timing of the upstream peak flow when the release from reservoirs is more dependent on the magnitude of the incoming annual peak flow and the water storage at the end of the previous year. This, consequently, adds more variability in reservoir releases as well as extreme peak flows in the delta when upstream flows have earlier annual peaks. Comparison between the top and bottom rows shows that the regulative effect of the water resource system is much larger than for mere irrigation expansion.

## 4.4 | Effects on the long-term annual timing of the peak flow to the delta

Change in the long-term timing of the annual peak flow can potentially disturb species in the delta that have life cycles that are adapted to peak flows at a particular time of year. High water in late spring provides rearing habitat for spring-spawned fishes such as sturgeon, northern pike (*Esox lucius*), and walleye (*Sander vitreus*; Paul, 2013). Under changing streamflow conditions, one crucial question is how much the long-term timing of the annual peak flow in the delta changes, given the fact that there is a water resource system in place. For this purpose, timing of the long-term annual peak flow to the delta was obtained under both historical flows and the nine selected changing conditions. By subtracting the expected annual peak timing under a changing condition from the corresponding historical value, the expected shift in the SRD's timing of the annual peak under current (top panel) and expanded irrigation (bottom panel) was calculated (Figure 6). Obviously, the timing of the long-term annual peak flow to the delta is more sensitive to changes in the upstream peak flow timing. Moreover, it is apparent that a reduction in upstream flow volume, even with historical annual peak flow timing, can considerably alter the timing of the annual peak flow to the delta (see [0,0] and [0, −25%] in the top row). Considering a specific flow condition in both top and bottom rows in the figure, it was revealed that an increase in irrigation area can slightly shift the timing of the long-term annual peak flow in the delta to both earlier and later dates, depending on the upstream flow realization. This divergent response is due to different releases from reservoirs, which are dependent on the antecedent storage and incoming flows from Alberta.

## 4.5 | Effects on the variation in annual peak flow magnitude and timing

Jardine et al. (2015) defined a perfectly rhythmic floodplain river as one that has a peak flow of identical magnitude at the same time every year. In their analysis of river systems from South America and Australia, they found that rivers with rhythmic floodplains have higher riparian vegetation productivity, higher fish species richness and less variable avian populations than those with less predictable peak flow events. Here, variation in annual peak flow magnitude and timing were measured as a proxy to understand how changes in upstream conditions can perturb the rhythmicity of the peak flow to the delta.

The variation in annual peak flow magnitude was quantified using the Coefficient of Variation ($CV_{max}$). For each streamflow realization within the nine streamflow conditions, peak flow magnitude was obtained for each year and $CV_{max}$ was calculated for the annual peak flows over a 31 year period. Each box in the figure represents the range of the $CV_{max}$ over 100 realizations (Figure 7). The variability of annual peak flow magnitude significantly increases as the timing of the upstream flow shifts to earlier dates. Considering unique streamflow conditions, with and without irrigation expansion, it can be argued that a larger irrigation area will increase the $CV_{max}$ of the

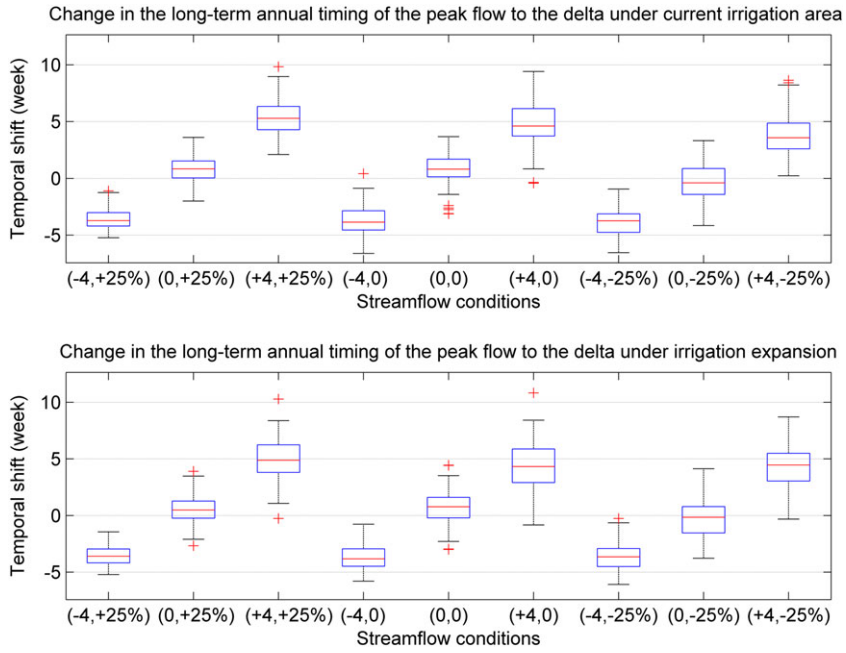


**FIGURE 6** Shift in the long-term annual timing of the peak flow to the delta for the nine selected scenarios of change in streamflow conditions under current (top row) and expanded irrigation (bottom row). Each box represents the variations of shift in the timing of the long-term annual peak flow over 100 realizations

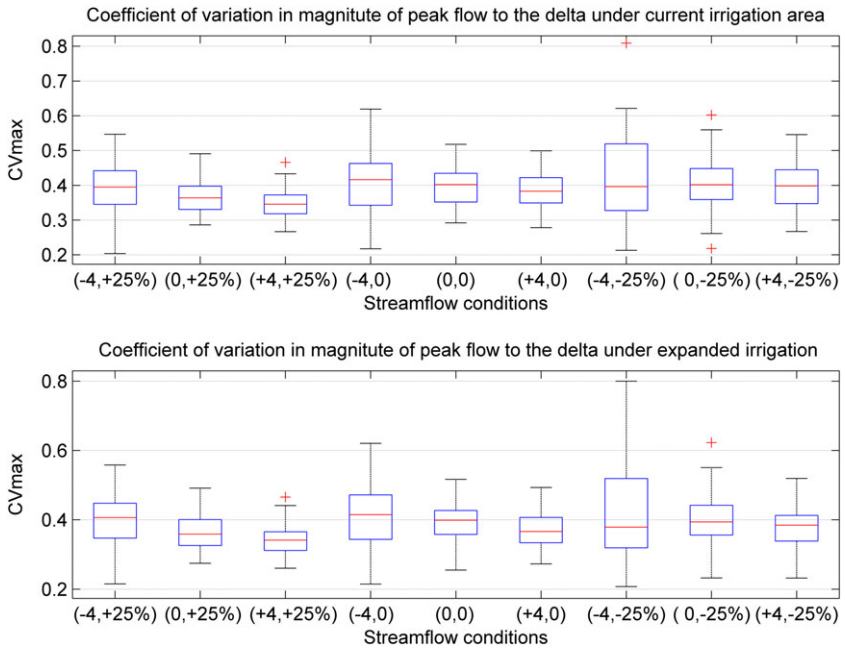


**FIGURE 7** The Coefficient of Variation (CVmax) of annual peak flow to the delta over a 31 year simulation period for the nine selected scenarios of change in streamflow conditions under current (top row) and expanded (bottom row) irrigation. Each box represents the range of the CVmax over 100 realizations

peak flow to the delta only under low upstream flow conditions with early peak flow timing. A decrease in rhythmicity in annual flood magnitude can significantly challenge biota in an area adapted to consistently high water levels from year to year as unpredictable flow conditions tend to favor generalist, tolerant biological assemblages (Jardine et al., 2015; Lytle & Poff, 2004).

The variability in annual peak flow timing was measured by finding the week of peak flow occurrence in the delta in each year and calculating its $CV_{max}$ over 31 years. $CV_{max}$ of timing of the annual peak flow for the nine streamflow conditions are shown in Figure 8, in which the boxplots represent the range of the $CV_{max}$ over 100 realizations. In contrast to peak flow magnitude, the variability in annual peak flow timing increases when timing of the upstream peak flow shifts to later dates. Moreover, Figure 8 shows that variability in annual peak flow timing is less sensitive to an increase in irrigation area than a change in upstream flow conditions. This is rather intuitive, as the timing of irrigation water demand or consumption does not vary much from one year to another; therefore, irrigation expansion does not change the variability of annual peak flow timing.

## 4.6 | Effects on the segmental streamflow frequencies

MacKinnon et al. (2015) identified five streamflow segments that portray different levels of connectivity and inundation among the SRD's wetlands and lakes—see Section 3.3. Under drought flow conditions

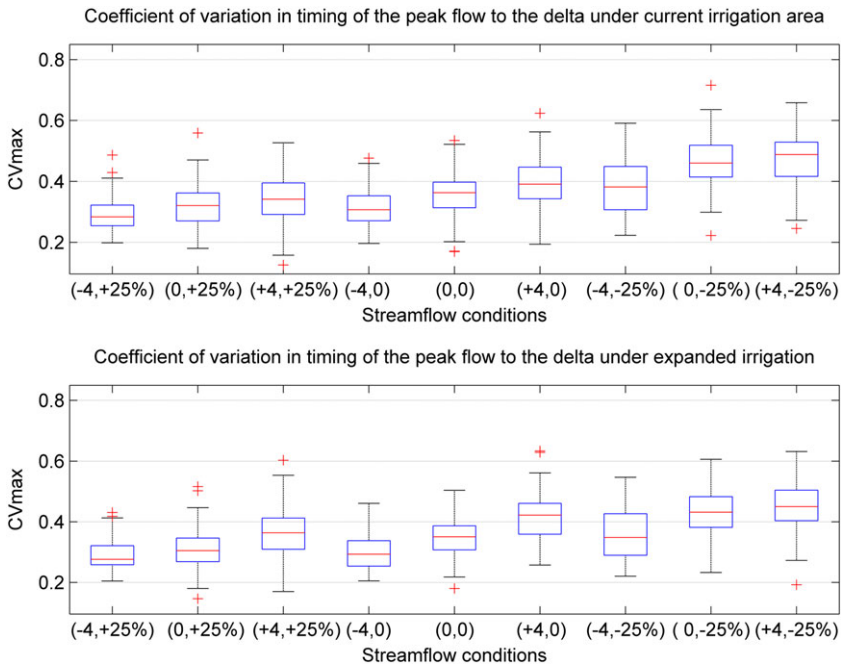


**FIGURE 8** The CVmax of timing of annual peak flow to the delta over a 31 year simulation period for the nine selected scenarios of change in streamflow conditions under current (top row) and expanded (bottom row) irrigation. Each box represents the range of the CVmax over 100 realizations. CVmax = Coefficient of Variation

(i.e., < 350 $m^3/s$), the main river channel is disconnected from all other parts of the drainage network, whereas under low flood conditions (i.e., between 350 and 500 $m^3/s$), connectivity reaches tributaries and riparian zones. Moderate flood conditions (i.e., between 500 and 1000 $m^3/s$) cause minor inundation that can cover up to 5% of the surface area. The level of connectivity increases under higher flow segments, reaching 20% and higher under high flood (i.e., between 1000 and 2000 $m^3/s$) conditions and extreme flood (i.e., ≥ 2000 $m^3/s$) conditions. Analysis of flow frequencies within these categories allows for better understanding of the frequency of connectivity between SRD lakes and the river mainstream. Such segmental flow frequencies can be obtained by calculating the ratio of streamflow incidents over a simulation period, in which the flow belongs to one of the segmental flow categories. The long-term streamflow frequencies for these streamflow conditions were obtained first for each realization and then averaged over 100 realizations to provide their expected long-term frequency. Figure 9 summarizes the results of this analysis without (top panel) and with (bottom panel) irrigation expansion. In brief, the expected long-term flow frequency is more sensitive to changes in annual flow volume than annual peak timing. Increase in irrigation area can also significantly change the long-term flow frequency within all the streamflow categories.

With no exception, irrigation expansion increases the flow frequency within the drought category and decreases frequency within all other categories under all selected scenarios of change in streamflow conditions. Overall, considering the nine streamflow conditions, the average of irrigation impacts on the expected long-term segmental frequencies are 17%, −17%, −12%, −27%, and −24% from drought to extreme-flood categories, respectively. This can be due to the fact that flows from the NSR can partly, but not fully, offset losses caused in the contributing flow from the SSR that has been abstracted by increased irrigation. Reduced connectivity limits access to diverse rearing habitats for fishes (Jardine et al., 2015) and can also lead to stranding in isolated water bodies during winter that often become anoxic with high ammonium concentrations (MacKinnon et al., 2015).

## 4.7 | Change in the long-term Surface Water Coverage Area during ice-free seasons

Changes in the long-term SWCA can have major ecohydrologic impacts, as it can alter the stability of existing aquatic habitats and the health of riparian ecosystems. A larger SWCA provides a greater diversity of aquatic habitats that can sustain various waterfowl species with diverse feeding behaviours (Baschuk, Koper, Wrubleski, & Goldsborough, 2012). To better understand the changes in the long-term SWCA due to changing streamflow and irrigation conditions, the weekly series of the inflows to the SRD during the ice-free seasons were converted into the corresponding SWCA series using the empirical equation provided in Sagin et al. (2015)—see Section 3.3 for the equation. A typical ice-free season in the delta extends from the last week of April to the last week of October, which was considered as the ice-free season throughout this study. Note that this duration remains unchanged between years and/or under changing conditions. As mentioned in Section 3.1, each flow condition represents an ensemble of streamflow realizations that have similar annual peak flow timing and volume but different flow time series. Changes in the long-term SWCA were estimated by calculating the ice-free SWCA for each year and averaging over 31 years to determine a long-term estimate for each realization. Consequently, the minimum, average, and maximum long-term estimates within 100 realizations were extracted. Figure 10 shows the percentages of change with respect to corresponding statistics during the historical period. The results show that

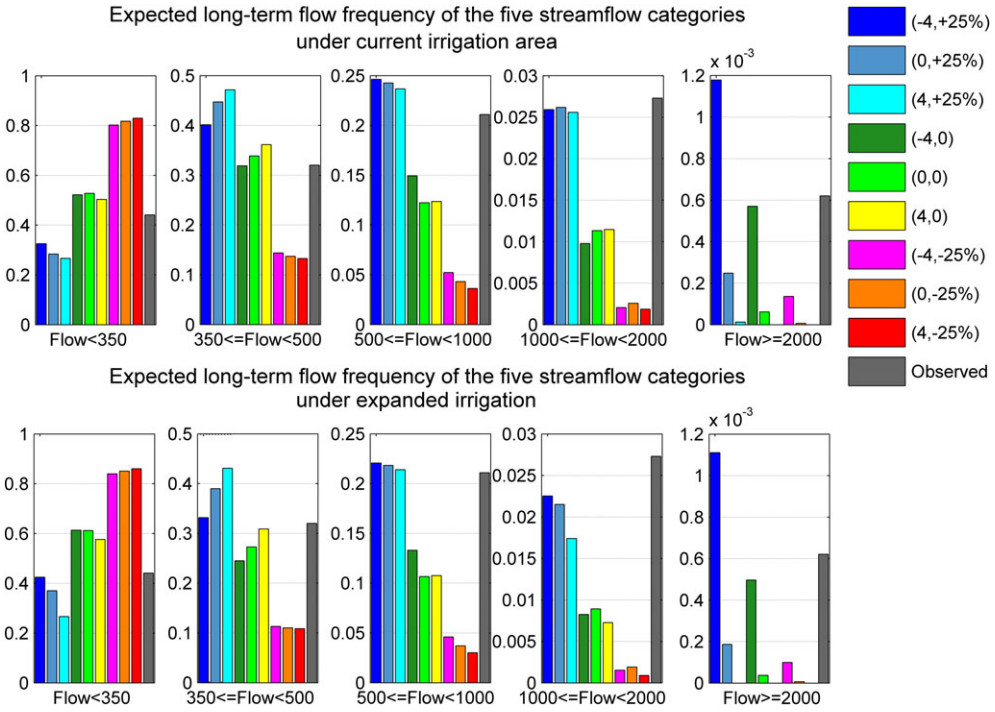


**FIGURE 9** Expected long-term flow frequency within five streamflow categories for observed as well as the nine selected scenarios of change in streamflow conditions, without (top row) and with (bottom row) irrigation expansion

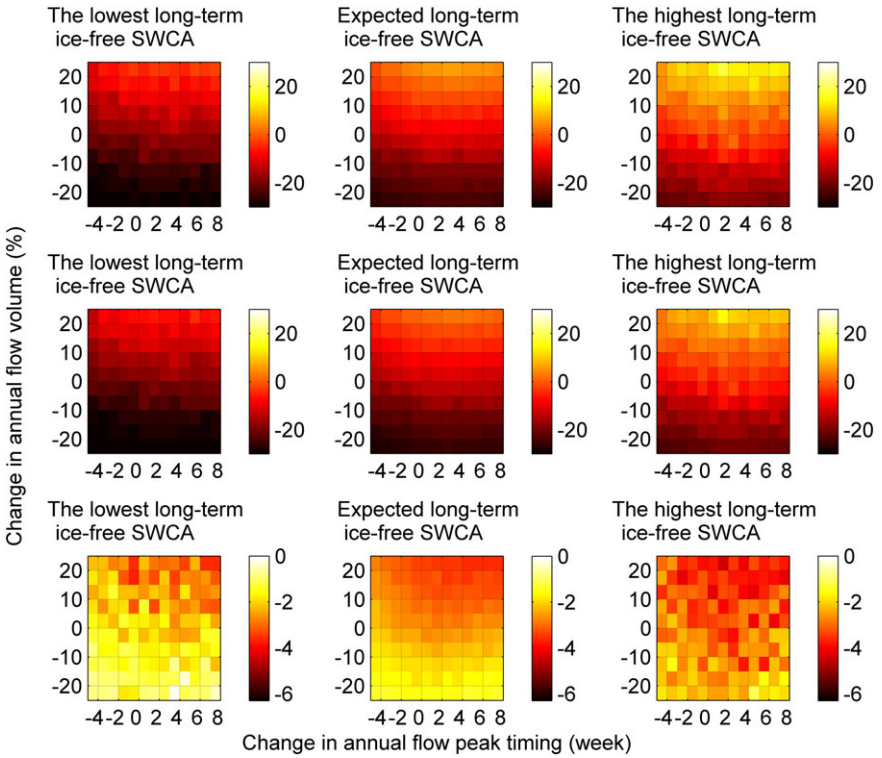


**FIGURE 10** Relative change (%) in the minimum, mean, and maximum long-term ice-free SWCA due to changing flow conditions (top row), changing flow conditions combined with irrigation expansion (middle row), and increasing irrigation area only (bottom row). The percentage of change in the long-term ice-free SWCA is shown in colour according to the colour-scale. SWCA = Surface Water Coverage Area

the long-term ice-free SWCA is more sensitive to changes in upstream annual flow volumes; nevertheless, the effects of changing volumes reduce from the lowest to the highest SWCA. During the lowest and average long-term SWCA, reduction in SWCA would be more prominent, if it is combined with an earlier timing of the peak. In particular, the lowest possible long-term SWCA can be reduced by up to 20% by only a 1 month earlier peak and no change in streamflow volume. The effect of irrigation expansion, in contrast, is more significant for the highest possible SWCA and under higher streamflow volume.

## 5 | SUMMARY AND CONCLUSIONS

Climate change and anthropogenic interventions can considerably alter streamflow conditions, which play a key role in affecting the health and biodiversity of freshwater ecosystems. Current approaches to assess the extent of hydrological alterations in freshwater ecosystems are commonly based on using top-down and/or bottom-up frameworks that ultimately require hydrological models to transfer climate realizations into streamflow sequences. Apart from the propagation of large uncertainties associated with using hydrological models into ecohydrological vulnerability assessment, hydrological models are still limited in representing changes in streamflow conditions due to human interventions (Borgomeo et al., 2015; Nazemi & Wheater, 2015a, 2015b). As a result, in this study, a fully bottom-up approach was implemented, in which streamflow realizations were generated stochastically without using any climate and/or hydrological models. The randomly generated streamflow realizations were able to accommodate a large ensemble of potential changes in annual volume and peak timing of streamflow entering the regional water resource system of Saskatchewan. These changes can be caused by both climate change and human interventions. We focused on the ecohydrological vulnerabilities of the SRD, which is located downstream of Saskatchewan's water resource system; therefore, any viable vulnerability assessment of this important ecosystem requires accounting for various human interventions within the province itself. At the moment, the proposal to increase the irrigated area 10-fold could potentially affect the streamflow entering the SRD.

Overall, the results show that the streamflow regime in the delta is more sensitive to change in upstream annual flow volume than timing of the peak and/or provincial irrigation expansion. Depending on the particular ecohydrological indicator, this sensitivity can be increased if it is combined with earlier or delayed timing of the peak; however, our results show that earlier timing of the peak, which is expected to occur in a warming climate (Pomeroy et al., 2009), can cause more vulnerability particularly in rhythmicity of the annual peak flow magnitude in the delta. Irrigation expansion can additionally decrease the magnitude and frequency of the long term and extreme peak flows entering the delta and can slightly change the timing of the long-term annual peak flow in the SRD, depending on the streamflow conditions. Moreover, irrigation expansion alters the frequency of average and low incoming flow to the delta, with the consequence of disconnecting more lakes and wetlands from the main channel system. Such changes can affect both water quantity and quality, and can influence the composition, structure, function, and diversity of aquatic and riparian ecosystems and significantly affect the life of the SRD's local residents (Abu et al., 2016). It was also shown that the effect of irrigation is greater during higher streamflow conditions, which means that irrigation expansion can limit the benefits that the SRD can gain from higher annual flow volumes. This portrays a need for policy adaptation and requires an explicit consideration of environmental flow demands in the delta. This is particularly relevant to regional water management.

We suggest further research be carried out to understand how alternative policies can balance the ecosystem needs in the delta with other demands under future changes in streamflow and irrigation expansion.

While the approach applied here provides robust estimates of ecohydrological vulnerability, some improvements can be made. First, many sources of interannual variability were not considered in this study. Most importantly, it was assumed that the growing and ice-free seasons do not vary annually. To overcome this limitation, it is required to evaluate the impact of natural climate variability and climate change on the irrigation demand as well as the length of growing and ice-free seasons. In addition, it was assumed that possibilities represented through the feasible ranges of change in the upstream streamflow regime have similar likelihoods of occurrence in the future. This assumption should be relaxed by using the results of the top-down impact assessment to identify the chance of possible future conditions in light of the available projections. Moreover, in this study a feasible range of change in long-term annual flow volume and peak flow timing was chosen to represent the combined effect of climate change, water resource management, as well as land use and land management change on upstream flow conditions. Therefore, the sign (decrease or increase) and magnitude of alteration in the characteristics of the SRD due to each of these drivers was not separately identified. In future studies, hydrological models can be used to distinguish between the effects of multiple drivers on the characteristics of the SRD, while recognizing uncertainty due to the continuous progression in hydrological models. With respect to streamflow reconstruction, it should be noted that NSR and SSR flows were reconstructed independently due to the limitation of linear regression in reconstructing the flow characteristics in space. Accordingly, there is a need for new developments to jointly reconstruct flows while preserving their spatial correlation, and capturing observed temporal structure and variability. Finally, it should be noted that changes in considered ecohydrologic indicators cannot entirely reveal the potential impacts on the ecosystem of the delta (Fung et al., 2013). As a result, there is an urgent need to correlate the exact changes in ecological characteristics with observed hydrological changes to better assess the vulnerability to future changes (Poff et al., 2010).

Regardless of these limitations, this study provides a new understanding of the vulnerability of one of the largest and most productive deltas in North America. The fully bottom-up approach implemented in this study is generic and can be used to assess the ecohydrological vulnerability in other freshwater ecosystems that are under pressure due to both climate and anthropogenic changes.

## ACKNOWLEDGMENTS

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