EVALUATING ESTIMATES OF CHANNEL FLOW IN A CONTINENTAL-SCALE LAKE-DOMINATED BASIN

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ABSTRACT

Accurate estimates of continental-scale channel flows are needed to understand spatiotemporal variability in water supplies and the water balance. At regional scales, models of connecting channel flows are commonly used to understand how variability in the water cycle propagates into engineering-oriented decisions related to water quantity and water quality management. Since 1958, deterministic monthly flows have been calculated for all of the connecting channels of the Great Lakes - St. Lawrence River system through a binational, multi-agency coordination process. Here, we review these historical estimates, most of which have never appeared (or appeared decades ago) in the peer-reviewed literature, and compare them to new estimates from a novel statistical water balance model. This new model was developed using a variety of water balance component estimates across the entire Great Lakes system, and includes an explicit expression of uncertainty. Our findings indicate that the historical range of deterministic channel flow estimates is similar to the range of uncertainty represented by our statistical water balance model. We also

find that historical internationally-coordinated flows for this massive lake and river system from the late 1990s through 2009 appear to be negatively biased, and may need to be revised. Our new statistical water balance model provides an ideal platform for implementing this revision, and other future updates to regional water balance information.

Keywords: channel flow; stage-discharge; uncertainty estimation; hydraulic model

INTRODUCTION

Monitoring and forecasting the water balance of large freshwater basins is a major challenge facing a range of engineering and scientific disciplines (Nijssen et al. 2001; Shiklomanov et al. 2006). Anthropogenic controls (Nilsson et al. 2005) and climate change (Milly et al. 2008) contribute to variability in energy and mass fluxes across aquatic systems (Peterson et al. 2002; Dai and Trenberth 2002), and differentiating these drivers is critical to robust water resources management planning. Accurately identifying origins of change in the water balance that lead to persistent water loss and drought, for example (Lofgren et al. 2013; Gronewold and Stow 2014), is a fundamental step in developing and implementing effective measures for ensuring sustainable long-term water supplies (Brown et al. 2011).

Of the large freshwater systems in North America, the St. Lawrence River (including the Laurentian Great Lakes) Basin is in many ways the most complex (figure 1). The river has a mean annual flow of 12,600 cubic meters per second (cms) near Quebec City, representing the second highest river discharge from the continent (Benke and Cushing 2011). The water surfaces of the Great Lakes have a collective area of 244,000 km^2, constitute roughly 30% of the areal extent of the upper basin (i.e. the basin domain upstream of the outlet of Lake Ontario), and encompass a significant portion of the international border between the United States and Canada (figure 1). Energy and mass fluxes across this system have a profound impact on the regional water balance (Lenters 2001; Quinn 2002; Assel et al. 2004) and climate (Notaro et al. 2015), and outflows from both Lake Superior and Lake Ontario are regulated under conditions of a US-Canada binational treaty administered by the International Joint Commission, or IJC (Lee et al. 1994; Clites and Quinn 2003). Finally, long-term dredging projects that maintain navigability in the channels that connect the Great Lakes have induced permanent changes in conveyance, flow rates, and water level differential between upstream and downstream lakes (Quinn 1985; Derecki 1985).

Over the past decade, there have been significant advances in monitoring and modeling the Great Lakes water balance that dovetail with legacy regional hydrometeorological data sets (Deacu et al. 2012; Hunter et al. 2015). Long-term continuous lake surface water elevation data from a network of gauging stations, for example, is publicly available and considered very robust (Gronewold et al. 2013). Similarly, multiple research studies have explored and, in some cases, led to implementation of methods for improving estimates of over-lake precipitation (Watkins et al. 2007; Holman et al. 2012; Lespinas et al. 2015), over-lake evaporation (Spence et al. 2011; Blanken et al. 2011; Spence et al. 2013; Fujisaki-Manome et al. 2017), and lateral tributary runoff into the lakes (Fry et al. 2013; Fry et al. 2014; Gaborit et al. 2017).

Here, we introduce a new approach to estimating monthly channel flows, using the Great Lakes as a representative case study. We compare and contrast our new approach to a set of legacy estimates, including those derived through a regional binational partnership, and those derived through hydraulic engineering models. In addition to filling a gap in research on the regional water balance, our analysis of connecting channel flows addresses a need for better understanding of how changes in those flows affect lake temperature, heat content, and ice formation (Schwab et al. 1999), circulation patterns (Beletsky et al. 2006; Anderson and Schwab 2013), water quality (Nichols et al. 1991), and the spread of invasive species (Schloesser and Nalepa 1994) across the Great Lakes. We focus our study on the Detroit River because there are several ongoing research questions that need to be answered about long-term changes in its flow regime, its role in changing water level differentials between Lake Michigan-Huron and Lake Erie (Gronewold and Stow 2014), and its role in recent proliferation of toxic algal blooms in Lake Erie's western basin (Quinn and Guerra 1986; Michalak et al. 2013; Obenour et al. 2014). The methods we describe are not necessarily restricted to applications on the Detroit River and we hope that, in future research, they can be applied to other connecting channels not only within the St. Lawrence - Great Lakes Basin, but in other large riverine systems around the world as well.

METHODS

To advance the state-of-the-art in regional hydraulic modeling and engineering practice, we introduce a new configuration of a recently-developed statistical water balance model for large lake systems (Gronewold et al. 2016). This model, commonly referred to as the Large Lake Statistical Water Balance Model (or L2SWBM), uses Bayesian inference to derive monthly channel flow estimates by resolving estimates of other water balance components (including, for example, over-lake precipitation and over-lake evaporation) and their intrinsic biases and uncertainties.

We then compare the new L2SWBM Detroit River flow estimates to those developed by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Gronewold and Fortin 2012; Gronewold et al. 2018). This *ad hoc* group (hereafter referred to as the 'Coordinating Committee') of government science agency representatives from both the US and Canada was formed in 1953 and has historically used a combination of stage-fall-discharge (SFD) models, 1-dimensional hydraulic models, expert opinion regarding knowledge of *in situ* channel conditions (including ice and weed formation), and other information sources to arrive at a single internationally-coordinated deterministic Detroit River discharge estimate.

Finally, we provide a representative example of three SFD relationships (Shiono et al. 1999) that have either been used in historical studies, or have been considered for use by Great Lakes regional water management practitioners and scientists (Quinn 1985), and are indicative of the models routinely evaluated by the Coordinating Committee. It is informative to note that application of SFD models to the Great Lakes, while a consistent component of regional water management practice, has rarely been documented in the peer-reviewed literature. There are also frequent debates within the regional hydraulic science and engineering community over whether SFD model formulations should be constrained by engineering theory, or if more novel model formulations (including those representing uncertainty) should be used to explain *in situ* channel discharge measurement variability. Our goal here is not to resolve these debates; rather, we intend to demonstrate that the intrinsic variability among alternate deterministic formulations of SFD relationships might be well explained by the variability expressed in a statistical water balance model. For further reading on historical Detroit River flow estimates, see Brunk (1968) and Quinn (1978).

Study area - Detroit River

The Detroit River runs from the southern end of Lake St. Clair to the northwest corner of Lake Erie (figure 2). It covers a distance of about 51 km, has a total fall of 0.9 m, and has an average discharge of roughly 5,200 cms. Most of the upper stretch of the river is a single narrow deep channel, while the lower reach (below Wyandotte) is broad with intermittent islands and shallows. Periodic maintenance dredging of the channel is needed to maintain a safe navigable depth. The lower portion of the river (from the Wyandotte to Gibraltar gauge) has not been used in discharge determination since the mid 1980s due to variability in channel roughness (and the challenges of quantifying that variability in models) related to proliferation of zebra and quagga mussels and subsequent changes in weed growth (Nalepa and Schloesser 1992)

The bottom of the Detroit River channel is predominantly bedrock and clay, and it is therefore commonly assumed that there has been no change in the river's conveyance following the completion of the last major navigation improvements (i.e. dredging) project in 1962 (Coordinating Committee 1988). Furthermore, a recent multi-year study commissioned by the IJC determined that while conveyance changes have taken place on the St. Clair River (between Lake Huron and Lake St. Clair) since the 1960s, there is no conclusive evidence of similar changes on the Detroit River (IJC 2009). These findings have important implications for model development and testing.

Data

Historical *in situ* Detroit River discharge measurements have been collected since the 1860s across multiple intermittent field campaigns, and along multiple reaches of the river (Coordinating Committee 1994). For this study, we employed measurements collected along the reach near Fort Wayne (figure 2) starting in 1962 because they represent the longest set of continuous measurements available since the conclusion of the navigation projects (Schmidt et al. 2009). More specifically, between 1962 and 1986, 229 instantaneous flow measurements were collected across 12 field campaigns at the Fort Wayne cross-section (near the Ft. Wayne gauge, see figure 2) by the U.S. Army Corps of Engineers (formerly the U.S. Lake Survey) using conventional mechanical current meters. It is informative to note that measurements between 1962 and 1968 were collected by the U.S. Lake Survey from relatively heavy barges, while measurements between 1973 and 1986 (using the same conventional meters) were collected by the U.S. Army Corps of Engineers from relatively light vessels; a discontinuity in monitoring protocol that may have contributed to variability in observed stage-discharge relationships. No flow measurements were collected in the Ft. Wayne cross-section of the river between 1986 and 1996. Beginning in 1996, flows were recorded by the U.S. Army Corps of Engineers using acoustic Doppler current profilers (ADCPs).

Historical water level measurements were collected with the historical discharge measurements at the Windmill Point (station 9044049) and Wyandotte (station 9044030) monitoring stations. These stations were originally installed by the U.S. Lake Survey in (respectively) 1897 and 1930, and are now maintained by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (COOPS). Continuously recording gauges were installed in 1952 at Windmill Point, and in 1957 at Wyandotte (Coordinating Committee 1978). The IJC, as part of its relatively recent International Upper Great Lakes Study (IUGLS), maintains and distributes all but the final three years of historical discharge data and corresponding water level measurements through its web page; the 2007-2009 data are available from the US Army Corps of Engineers, Detroit District. We employed these historical records in the model calibration procedures described in the *calibration and simulation* section.

For the simulation phase of our study, we utilized Windmill Point and Wyandotte water level data maintained and distributed by COOPS, however it is important to note that these stage records are available at different temporal resolutions and across different historical periods. For example, the COOPS historical records include nearly continuous hourly stage measurements at Windmill Point beginning in 1970, nearly continuous daily mean stage measurements beginning in 1950, and monthly mean stage measurements beginning in 1897. Similarly, continuous hourly stage measurements are available from COOPS at Wyandotte beginning in 1970, while continuous daily and monthly measurements are available beginning in 1962. We downloaded these datasets directly from the COOPS web server.

It is reasonable to assume that measurement procedures across these periods had varying degrees of bias and uncertainty. In addition, each campaign varied in length and intensity; during some campaigns, multiple measurements were collected on a single day, and measurements were repeated for several days in a row (figure 3). In other periods, measurements were collected less frequently. Further discussion on our approach to addressing these inconsistencies is included in the *calibration and simulation* section.

Statistical water balance model (L2SWBM)

The focal point of our study is the development and evaluation of a new set of estimates of historical monthly Detroit River discharge using the L2SWBM (Gronewold et al. 2016). A prototype of the L2SWBM was recently developed through a partnership between the NOAA Great Lakes Environmental Research Laboratory (GLERL) and the University of Michigan Cooperative Institute for Great Lakes Research (CIGLR), and was designed to simulate Bayesian posterior probability distributions for each of the major components of the Great Lakes water balance at monthly time scales. An important feature of the L2SWBM is that it reconciles long-term measurements of lake storage (using a simple lake water balance model) with readily-available sources of information (including measurements and process model-based estimates) of each water balance component.

For this study, we ran the L2SWBM over a historical period from 1960 to 2015 across all of the Great Lakes. Specifically, we ran two configurations of the L2SWBM; we ran the first (L2SWBM-A) independently of historical Detroit River estimates from the Coordinating Committee (described in the following section), and we ran the second (L2SWBM-B) with an assimilation of those estimates. We compare these two configurations to better understand the extent to which information about other components of the Great Lakes water balance might help reduce uncertainty and bias in estimates of Detroit River discharge, and the extent to which Coordinating Committee estimates are consistent with the L2SWBM (and, by association, with the entire Great Lakes water balance).

Internationally-coordinated estimates

For the past several decades, the most widely-distributed estimates of historical Detroit River discharge are those developed by the Coordinating Committee. The methodology employed by this group, however, is not documented in the peer-reviewed literature, though it is distributed in publicly-available technical reports. In general, the Committee has aggregated a combination of SFD and unsteady flow models developed independently by US and Canadian federal agency representatives, and has then combined those estimates while considering the integrity of each individual model. It is also our understanding that the members of the Coordinating Committee typically use the lowest daily flow value as a proxy for the entire monthly flow average in periods when ice is prevalent and when the full suite of daily flow values may be biased. During other periods, the Committee has used estimates of St. Clair River discharge and water supplies to Lake St. Clair to estimate Detroit River discharge. We believe there is a need for the Coordinating Committee to more formally document these methods. In the following section, we provide a representative example of calculations for three types of SFD relationships that are either used, or considered for use by, the Coordinating Committee and other regional practitioners.

Representative stage-fall-discharge (SFD) models

SFD models: description

Following common assumptions for wide channels with gradually varied flow (Bakhmeteff 1932; Chow 1959; Quinn 1964; Schmidt and Yen 2008) in which backwater effects lead to different falls for a given depth (Hidayat et al. 2011), historical SFD-based models of Detroit River flow are often based (Fay and Kerslake 2009) on the following formulation (customized to the Windmill Point to Wyandotte reach) relating discharge (Q, in cms), stage (z, in m), and channel bottom elevation (y, in m):

$$Q = c((z_{wp} + z_{wy})/2 - y_m)^d * (z_{wp} - z_{wy})^f \quad (1)$$

where c is an empirical constant related to channel length and Manning's roughness, and z_{wp} and z_{wy} are the surface water elevations at Windmill Point and Wyandotte, respectively (in meters). The fall (hereafter identified as F) is $z_{wp} - z_{wy}$, y_m is the average elevation of the channel bottom in the Windmill Point to Wyandotte reach, and d and f are depth and fall exponents, respectively.

Three modifications of this model have either been deployed, or considered for deployment, in the Detroit River. The first (which we hereafter refer to as the 'multiple linear regression' or 'mlr' method) follows the assumption that c, d, and f (equation 1) are unknown parameters, and that y_m is 167m. We recognize that the assumption of a fixed value for y_m has potential implications for estimates of other model parameters, however previous studies have used similar values (typically ranging between 164 and 168m). It is unlikely that alternate values, or that encoding y_m as an uncertain parameter, would change the inferred value of the depth exponent d because the Detroit River is relatively deep. Taking the natural logarithm of both sides of equation 1 yields the following:

$$\ln Q = \ln c + d \ln((z_{wp} + z_{wy})/2 - 167) + f \ln(z_{zp} - z_{wy}) \tag{2}$$

from which parameters c, d, and f can be estimated. Historically, these values have been estimated using classical regression techniques, however the specific application of these methods to the Great Lakes is not well-documented in the peer-reviewed literature.

Our second SFD model (hereafter referred to as the 'Qn/Fn' method) is based on relating 'normal' fall F_n (i.e. constant over time, with no backwater effects) to associated channel flows Q_n as (Quinn 1964):

$$Q_n = c((z_{wp} + z_{wy})/2 - y_m)^d * F_n^f \tag{3}$$

where y_m = 167. Dividing equation 1 by equation 3 yields the following rating equation:

$$Q/Q_n = (F/F_n)^f \tag{4}$$

which allows estimates of Q for any given fall F, conditioned on a calculated value of Q_n and F_n, and an estimate of f. To calculate Q for any given fall F, we estimated parameters c and d in equation 3 by taking the logarithm of both sides of equation 3 (in which F_n is a constant):

$$\ln Q_n = \ln c + d \ln((z_{wp} + z_{wy})/2 - y_m) \tag{5}$$

and employing regression analyses procedures described in the *calibration and simulation* section.

Next, we calculated average fall, F_n, and in doing so accommodated the observation (figure 3) that the fall is not consistent over the period of record. More specifically, we note a discernible change in fall for average stage values above and below roughly 175 m (figure 4). We confirmed this observation using the `changepoint` package (Killick and Eckley 2014) in the `R` statistical software environment (R core team 2017), which indicated a value of F_n = 0.325 m for average stage values less than 175.1 m, and a value of F_n = 0.383 m for average stage values greater than or equal to 175.1 m. The change in fall through this section of the Detroit River most likely reflects a natural change in its hydraulic regime above an elevation of 175 m due to an increase in channel surface width and depth at the Wyandotte end of the reach; the channel surface width at the Windmill Point end, in contrast, is constrained. Finally, we solve for f by taking the logarithm of both sides of equation 4, and employing linear regression procedures described in the *calibration and simulation* section.

Our third variation of the SFD model is adapted from procedures outlined by the International Standards Organization (ISO) in Geneva, Switzerland (International Standards Organization 2001). It is our understanding that this approach is being considered for operational implementation among regional water management authorities; this study provides one of the first experimental applications of the approach to the Great Lakes region. This approach uses two or more water level gauges, and empirical relationships between water level and discharge for a constant fall, to simulate flows. Rather than trying to fit the discharge to a single equation, a set of curves is derived and the relationship between the two curves is used to predict flow, based on the fall in the reach and the ratio of the discharge resulting from that fall. The relationship between gauge height and discharge forms the basis for adjusting the computed flow. Details of our ISO methodology are included in the Appendix.

SFD models: calibration and simulation

We calibrated (i.e. estimated parameter values for) each SFD model using the historical data described in the Data section, and the `lm` function (for fitting linear models using regression) in the `R` statistical software package (R core team 2017). While the hardware and software packages we employed for this step are (when compared to tools employed for historical Detroit River flows) relatively new, we made every effort to replicate the basic theory and modeling philosophies that have been employed, informally, in historical Great Lakes hydraulic engineering practice. We began by calibrating all models to the entire period of record. We then calibrated each model separately to the 1962 to 1986 period and the 1996 to 2009 period to accommodate potentially significant changes in observed SFD relationships. We recognize that more robust approaches might include explicit quantification and differentiation of measurement bias and uncertainty from model parameter uncertainty. Here, we followed a methodology that is consistent with conventional practice, and hope to implement alternative methods in future research. Our corresponding `R` code is included in the Appendix for reference.

We used each calibrated model to simulate Detroit River discharge using the historical Windmill Point (Station No. 9044049) and Wyandotte (Station No. 9044030) stage measurements described in the Data section. These stage records are available at different temporal resolutions and across different historical periods.

In light of the various temporal resolutions of historical stage data, we simulated Detroit River discharge with the SFD models using both daily and monthly stage measurements, while recognizing that the parameters of our SFD models are conditioned on discharge measurements reflecting channel conditions over a short (i.e. roughly hourly) time period. We use the currently available daily and monthly stage measurements to simulate discharge from the calibrated SFD models to follow what we believe to be conventional practice in the Great Lakes regional operational water management community. We also note that there are multiple missing daily stage values from the NOAA NOS COOPs record (about 130 out of the roughly 17,400 daily values between 1962 and 2009 are missing). Rather than infill these values, we simply omitted from our results any months in which there was missing daily data. For months with a complete record of daily stage values, we simulated discharge for each corresponding day and then calculated the monthly average discharge. We then used the monthly-average stage measurements to provide a basis for comparison and to assess the magnitude of bias and variability introduced when calibration data and simulation data are aggregated to different temporal scales. One monthly gauge value was missing from the historical record (May 1977 for the Wyandotte gauge). We infilled this one value using linear interpolation.

Finally, we recognize that explicit quantification of uncertainty in the SFD model-based simulations is desirable (Westerberg et al. 2011; Domeneghetti et al. 2012). However, rather than express uncertainty in the SFD model results, we followed conventional practice by calculating deterministic SFD model simulations, and comparing them to the deterministic estimates developed by the Coordinating Committee and, ultimately, to the probabilistic results from the L2SWBM.

RESULTS AND DISCUSSION

A visual comparison between the time series of Detroit River discharge estimates from configuration A of the L2SWBM (L2SWBM-A), from the Coordinating Committee, and from our three representative SFD algorithms (Figure 5) indicates that all five estimates are relatively consistent, with two important exceptions. First, we note that the L2SWBM includes an explicit expression of uncertainty that, for most of the period of record, explains nearly all of the variability among the other four estimates. This finding is important because it suggests that the uncertainty bounds of the L2SWBM encompass the range of outcomes from the SFD models. For further discussion, see our comparison between SFD model simulations using daily and monthly average stage values, and our assessment of SFD model parameters in the Appendix.

Second, we note the profound impact of seasonal ice formation in the Lake St. Clair corridor (Derecki and Quinn 1986; Derecki and Quinn 1987) and the varying degrees to which different modeling approaches reflect those impacts. Through the 1960s, 1970s, and 1980s, for example, the internationally-coordinated estimates and the L2SWBM-A reflect significant mid-winter declines in Detroit River discharge coinciding with ice formation, but in many years (e.g. 1976, 1977, 1978, and 1979) these dynamics are not reflected in SFD models. We also observe a noticeable decline in the occurrence and severity of seasonal ice-related flow anomalies through the 1990s and 2000s in the L2SWBM and internationally-coordinated estimates. This finding is consistent with previous research on changes in ice cover across the Great Lakes region over the past several decades (Wang et al. 2012; Bai et al. 2015; Mason et al. 2016).

The intercomparison of the long-term time series from each discharge estimate (i.e. Figure 5) also provides a basis for evaluating bias in historical estimates relative to the new L2SWBM estimates. We use the L2SWBM as a basis for assessing bias not only because it includes an expression of uncertainty (and therefore supports a probabilistic calculation of bias), but also because it was explicitly designed to be faithful to the long-term water balance of the entire Great Lakes system. Understanding how biases in historical Detroit River discharge estimates might lead to an imbalance in regional water supply simulations and forecasts is critical to improving long-term water resources management planning.

An explicit graphical summary of bias (relative to the L2SWBM) over time (Figure 6) indicates that, throughout much of the 1960s, 1970s, and 1980s, the ISO model has a very strong positive bias, while from the late 1990s to 2009, all SFD models and the internationally-coordinated estimates persistently underestimate discharge. Note that many of the spikes in positive bias for the SFD models coincide with ice-induced discharge anomalies. Bias in both the mlr model and Qn/Fn models (bottom-left and top-left, respectively, Figure 6) is less pronounced than in the ISO model from the early 1960s through the mid 1990s.

Some insight into the origins of relative bias in the SFD models can be derived from a comparison between simulated discharge from the calibrated SFD models (i.e. fitted discharge) and historical *in situ* discharge measurements (top panel, Figure 7). Inspection of the SFD model residuals (bottom panel, Figure 7) reveals these discontinuities and patterns more clearly, and indicates that discontinuities in model skill over time might warrant separate models (or separate model calibrations) for different periods in the historical record. Indeed, it is our understanding that the Coordinating Committee adopts this practice. Results of the SFD model calibration, however, while informative, serve as a basis for understanding only the skill of the SFD models in simulating the relatively sparse historical *in situ* discharge measurement record (i.e. Figure 3). For a related discussion on addressing discontinuities in stage-discharge relationships, see Gessler et al. (1998).

Importantly, we find that the coordinated estimates (bottom-right, Figure 6), most likely due to the processes adopted by the Coordinating Committee, are unbiased relative to the L2SWBM-A for most of the period from the late 1970s to the late 1990s. However, in the early 1960s and 2000s, the coordinated estimates appear to be negatively biased relative to the L2SWBM-A. The chronic relative bias in the SFD models and the internationally-coordinated estimates from the late 1990s through 2009 underscores the strong likelihood that the internationally-coordinated estimates (and the SFD models on which they are based) systematically underestimate discharge during this period.

Developing water supply estimates that are faithful to a region's long-term water balance should be a fundamental component of robust water resources management planning. Similar arguments have been proposed for ensuring fidelity with regional land-lake-atmosphere energy fluxes (Lofgren and Gronewold 2013; Lofgren et al. 2013). The hydraulic continuity of the Laurentian Great Lakes system provides an opportunity to test the relative benefits of modeling channel flows from a discrete channel-only perspective, to those from a holistic water balance perspective. Indeed, the tendency of the internationally-coordinated Detroit River discharge estimates to gravitate away from the values from the SFD models and towards the values from the L2SWBM suggests that the international coordination process adds significant value. However, we find that even further value can be added by assimilating these internationally-coordinated values into the L2SWBM (Figure 8). One of the benefits of this approach is the establishment of a new historical record with an explicit expression of uncertainty that is faithful to the regional water balance, and one in which uncertainties are significantly reduced relative to those from the L2SWBM-B. In future research, it will be important to assess how these uncertainties impact both bias and uncertainty in other L2SWBM-derived estimates of the major components of the regional water balance.

CONCLUSIONS

The established practice of running multiple independent models for simulating large channel flows, and then reconciling differences among those models through ad hoc negotiations within the Great Lakes modeling community, appears to be a reasonable but perhaps outdated approach to establishing a long-term historical record. This approach does, however, appear to be particularly effective in diminishing, but not entirely eliminating, sources of both decadal and seasonal (i.e. ice-related) biases in conventional SFD models.

We have also shown that reconciliation of the long-term water balance across the Great Lakes system through application of the L2SWBM has a direct impact on historical channel flow estimates. Using the newly-developed L2SWBM as a tool for blending multiple deterministic models into a probabilistic ensemble also represents a shift from the historical dialogue focusing on debates over approaches to appropriately selecting and calibrating SFD models, and quantifying uncertainty in historical *in situ* data, to a more contemporary dialogue focused on appropriate weighting or discounting of multiple sources of information about the entire Great Lakes hydrologic cycle in a state-of-the-art statistical water balance model.

Considerable effort might be put towards identifying appropriate methods for disaggregation of the historical records into different time periods (based on discontinuities in monitoring protocols), and that doing so can reduce long-term biases (see figure 6, bottom right), however the value of this effort may diminish if probabilistic ensemble methods are employed. The L2SWBM has the additional advantage of extending over a long period of record, and of explicitly quantifying time-varying uncertainty in each water balance component over that period. Finally, our analysis indicates that internationally coordinated flows appear to be underestimated in the Detroit River relative to the flow estimates from the L2SWBM for the period from the late 1990s through 2009. This finding is important in part because the L2SWBM is, by design, faithful to the water balance of the entire Great Lakes system (including estimates of water balance components for precipitation and evaporation), and also because the L2SWBM and internationally coordinated flow estimates are rather consistent before this time period. We therefore suggest the Coordinating Committee consider recomputing flows for the late 1990s through 2009 using the L2SWBM-based approach prescribed in this study.

SUPPLEMENTAL DATA

An Appendix containing additional information on methodology is available online in the ASCE library (ascelibrary.org).

DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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List of Figures

Figure 1

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Figure 2


Detroit River
Michigan
Windmill Point
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Lake
St. Clair
Detroit
Ambassador Bridge
Ft. Wayne Gauge
Windsor
Ft. Wayne Cross Section
Ontario
Wyandotte
Gauge
Gibraltar
Gauge
Lake Superior
Lake
Huron
Lake Michigan
Lake Erie
N
Kilometers
0
5
10
Canada
United States
Lake Erie

Figure 3

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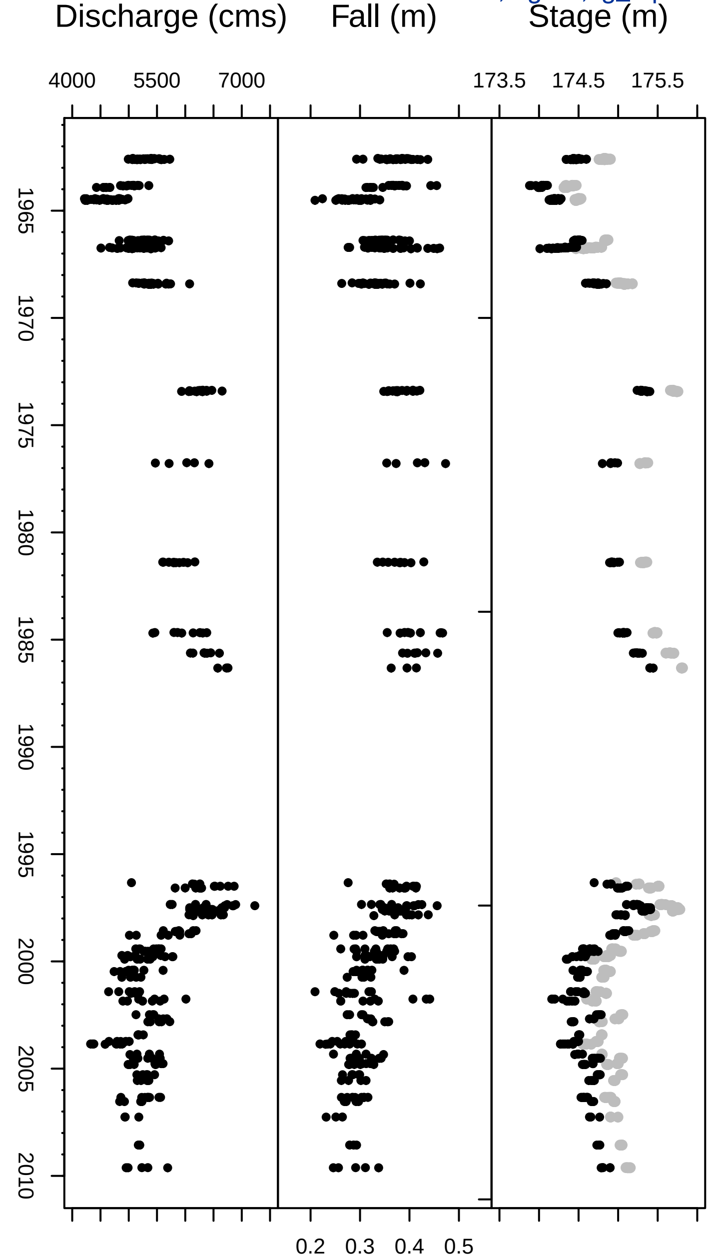
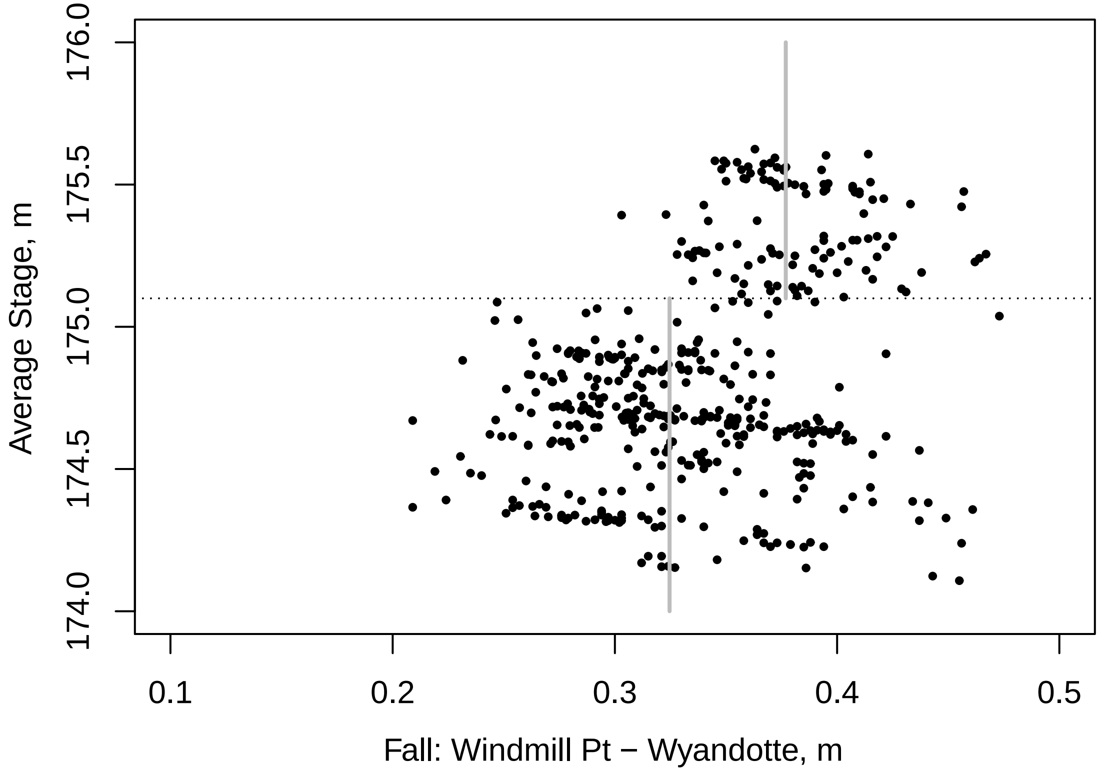


Figure 4



Average Stage, m
176.0
175.5
175.0
174.5
174.0
0.1
0.2
0.3
0.4
0.5
Fall: Windmill Pt − Wyandotte, m

Figure 5

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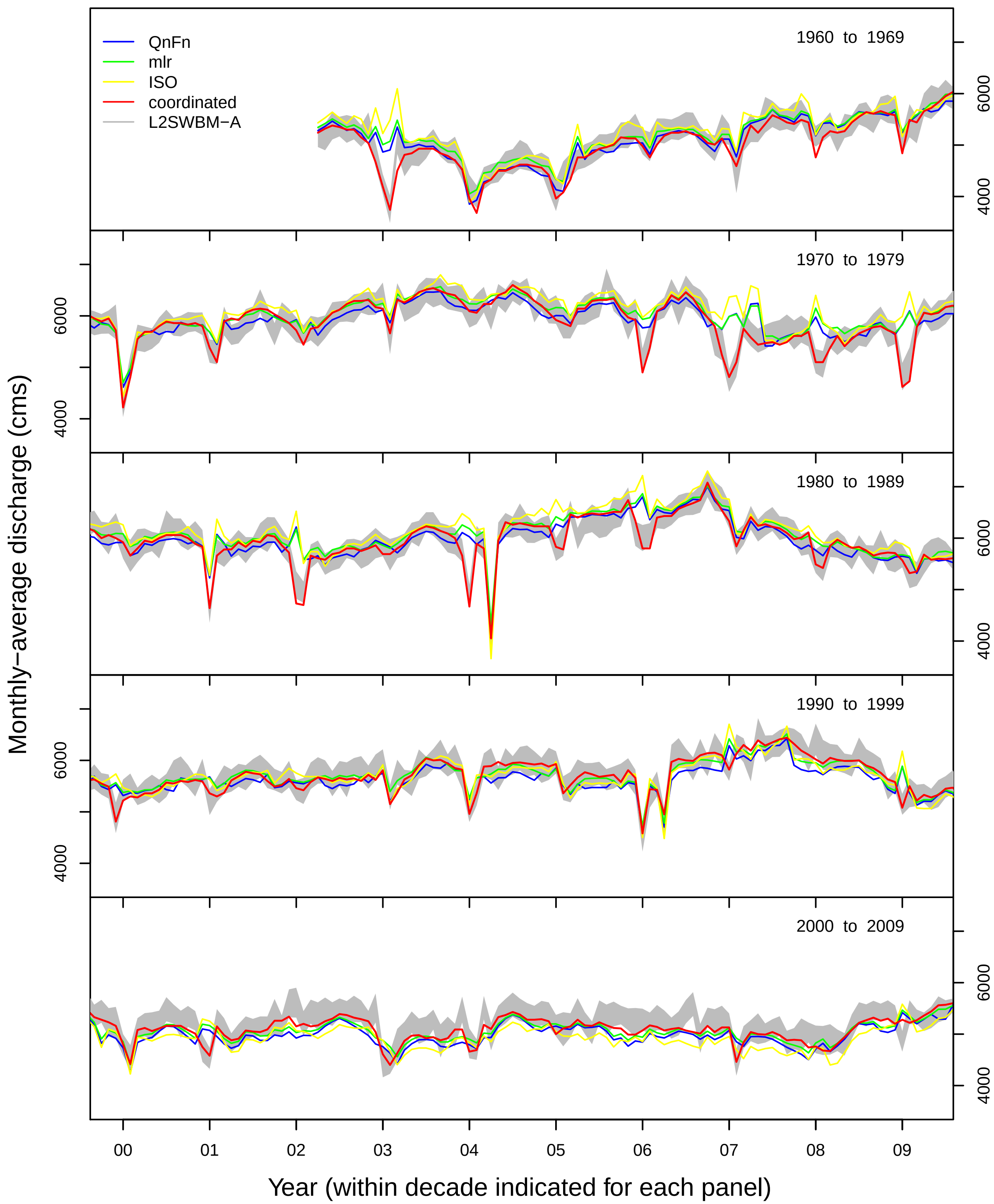

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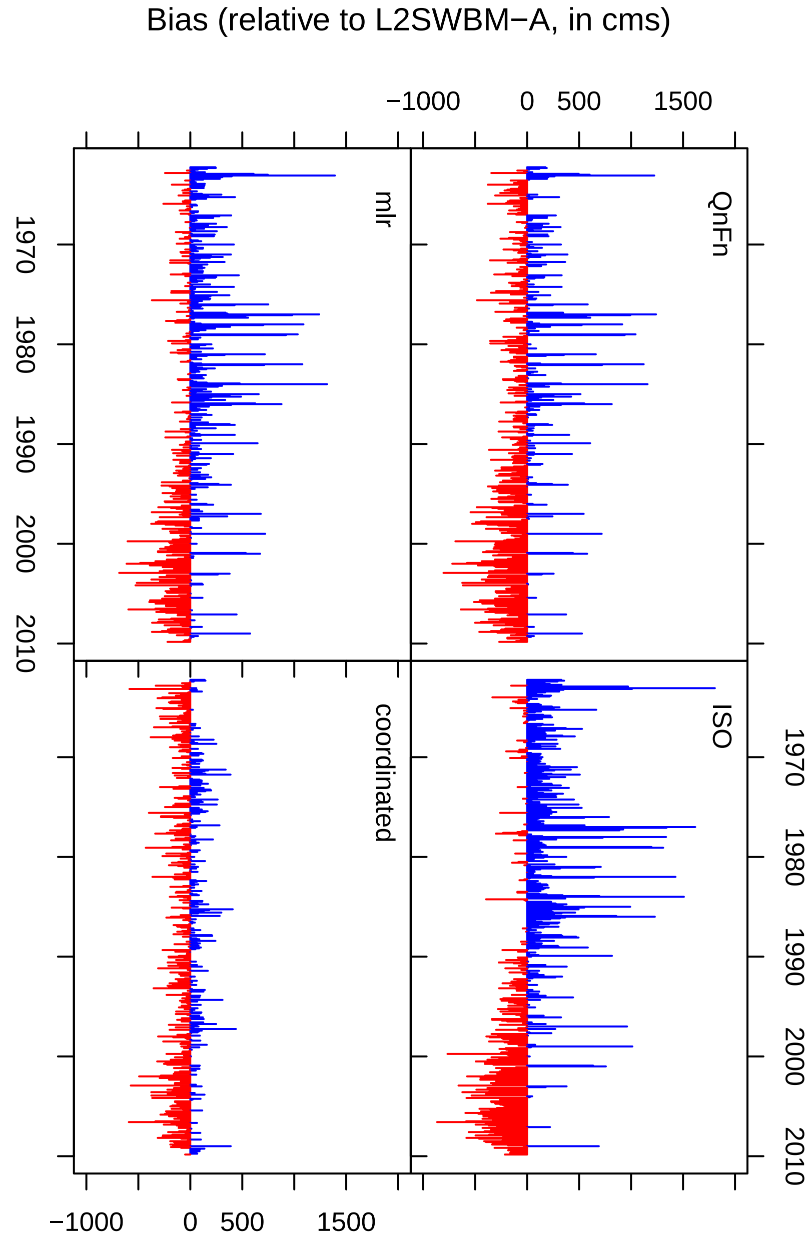

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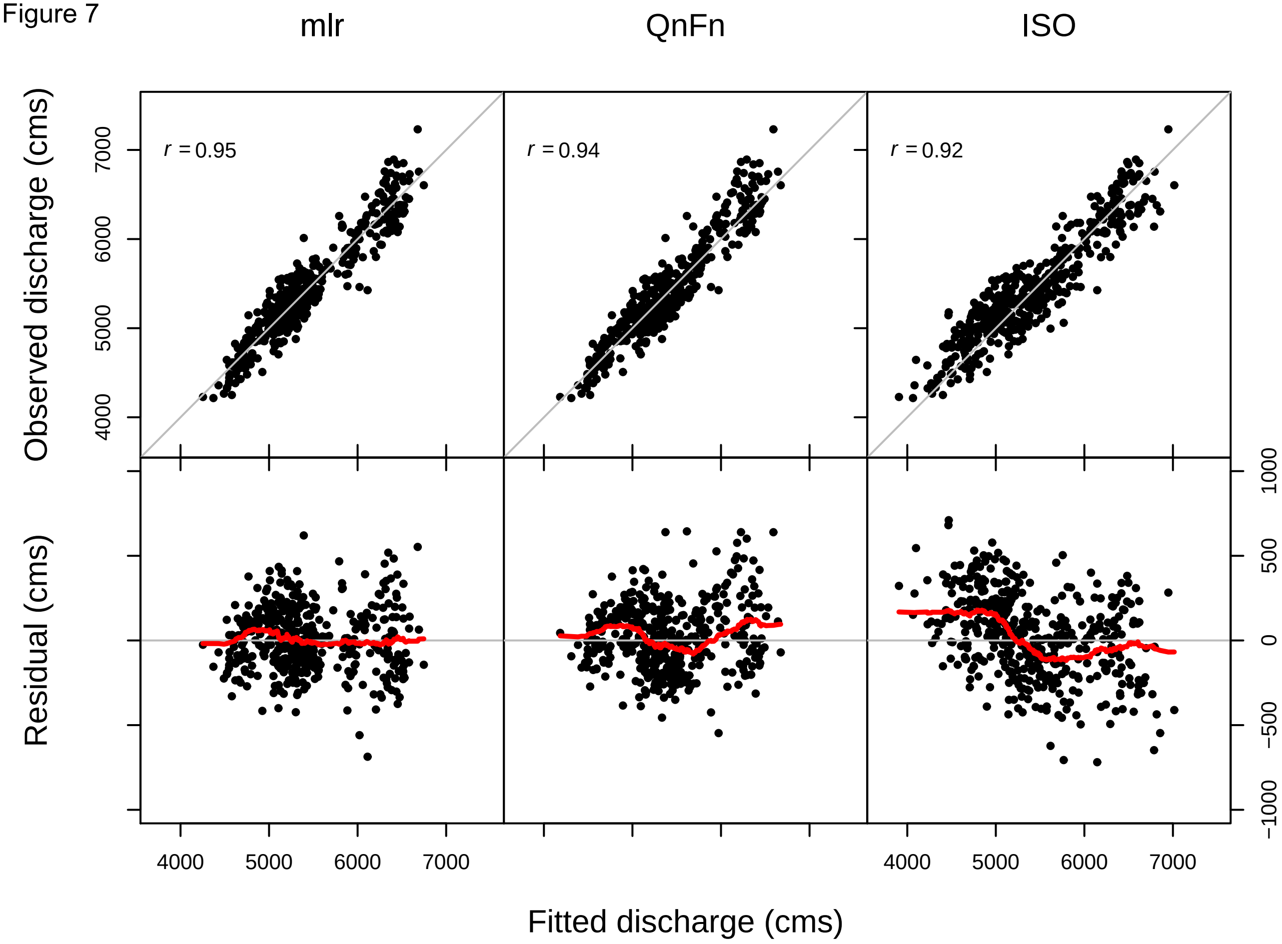

Figure 8

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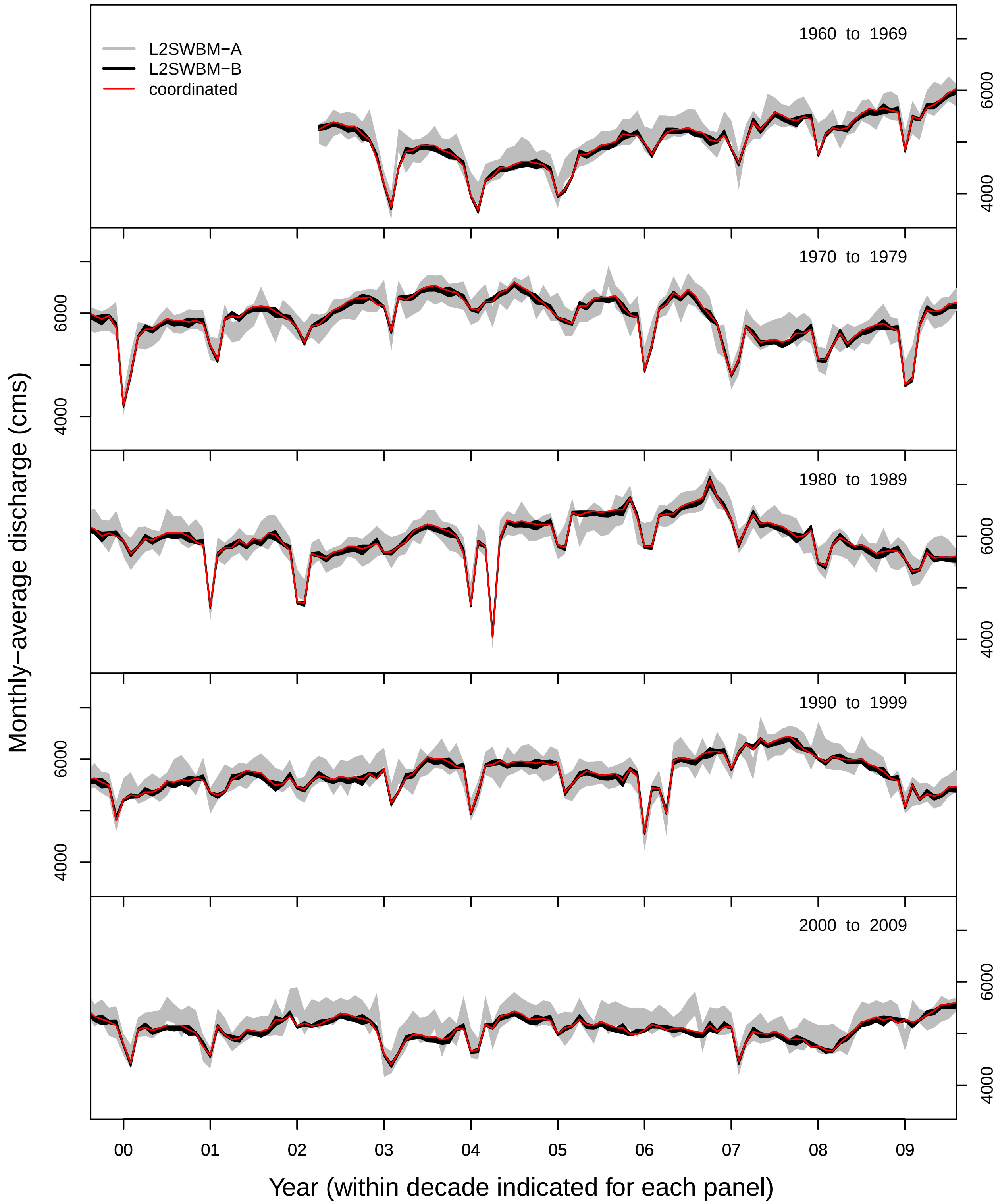

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