Error Analysis of Wind Effects on Natural Flow Estimation

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Abstract: When a large reservoir is fed by many tributaries, the measurement of reservoir inflow is a difficult task. For a hydroelectric reservoir, the estimation of natural inflow is required to optimize hydropower production without compromising environmental and infrastructure safety. This can be accomplished using the water balance equation (WBE). An important input of this equation is water levels measured from the reservoir of interest. However, the water-level measurements obtained from limnimetric gauges are affected by wind. Water-surface fluctuations caused by this meteorological forcing are carried over in the WBE. Consequently, natural inflow's signal may become noisy. On an hourly or daily basis, the wind-induced errors in natural inflow may become significant enough to make a reasonable estimation of real-time values impossible. This paper uses unsteady- and steady-state hydrodynamic modeling to estimate the WBE short-term errors originating from wind effect in the natural inflow of the reservoir. A hydrodynamic model calibrated with in situ observations has been used for this purpose in the Gouin Reservoir case study in Quebec, Canada. These results show that using a steady-state approximation can underestimate the effect of wind on daily estimates of the natural inflow because of the neglected seiches and inertial forces related to wind effect. **DOI:** 10.1061/(ASCE)HE.1943-5584.0001481.

Author keywords: Water balance equation; Wind; Natural flow error; Hydrodynamic model; Hydroelectric reservoir.

Introduction

Management of a hydroelectric power plant requires the collection and the analysis of multiple data at the reservoir of interest. In fact, one of the most important data for the water resources manager is the natural inflow of the hydroelectric reservoir. This type of data can be defined as the unregulated water inflow that supplies a reservoir during a given time interval. In other words, it is the summation of all the reservoir inflows except the regulated inflows originating from the outflow of an upstream reservoir. First, they are used as input data in a variety of hydrological studies to perform the design of various hydraulic structures. Furthermore, in hydrologic prediction applications, daily natural inflows A_n can be used as reference data to calibrate rainfall/runoff deterministic hydrologic model. For example, Hydro-Québec (the power corporation of Québec, Canada) uses one such model to simulate the predicted natural inflows A_p from meteorological data such as temperature and precipitation. This prediction is used by Hydro-Québec (Haché et al. 2003) to establish operation rules for reservoir to optimally manage the water resources while considering the safety of structures and environmental constraints. In addition, it also helps to plan the addition or maintenance of equipment to ensure the long-term satisfaction of electrical demand.

To obtain effective predicted flows A_p, the quality of daily natural inflows A_n needs to be high because they are used as reference data for the hydrologic model calibration. Unfortunately, in reference to the study area, it may be difficult to obtain a reliable time series of natural inflows. In fact, natural inflow A_n depends on hydrometeorological factors such as direct precipitation on the reservoir, snowmelt, inflow from unregulated tributaries, runoff from the catchment area, evaporation, and groundwater flow.

To adequately measure natural flow, it is necessary to instrument a watershed to measure on a daily basis each of the aforementioned hydrometeorological factors. However, some of these hydrometeorological factors such as inflows for all the tributaries and groundwater contribution are difficult to measure on a day-to-day basis (Hosseinpour et al. 2014). For instance, it would be too costly and/or unfeasible to install and maintain stream gauges on an important number of tributaries for each large reservoir that Hydro-Québec has to manage, especially if they are located in barren areas. Furthermore, stream gauges would not necessarily be adequate to measure runoff, evaporation, and precipitation. As such, to quantify the natural inflows A_n without measuring each hydrometeorological term described earlier, Hydro-Québec conducts daily operational water balance equation (WBE) calculations every day. This equation consists of applying mass balance conservation at the reservoir of interest. It can be expressed by

$$A_n = Q_{\mathrm{AV}} - Q_{\mathrm{AM}} + \Delta S \tag{1}$$

$$\Delta S = V_t - V_{t-1} = F_{\mathrm{storage}}(N_{c,t}) - F_{\mathrm{storage}}(N_{c,t-1}) \tag{2}$$

$$N_{c,t} = N_{c,t-1} + C(L_{1,t} - L_{1,t-1}, L_{2,t} - L_{2,t-1}, L_{3,t} - L_{3,t-1}, \ldots, L_{n,t} - L_{n,t-1}) \tag{3}$$

where Q_{AM} = regulated inflow at the reservoir of interest coming from the outflow of an upstream reservoir. This variable is estimated using the same method as Q_{AV} but for the upstream reservoir. However, the estimation of Q_{AM} needs to account for the routing from the reach joining the reservoirs. When there is no upstream reservoir, this term is null; Q_{AV} = outflow from the spillway and the power plant of the reservoir. The outflow is not measured

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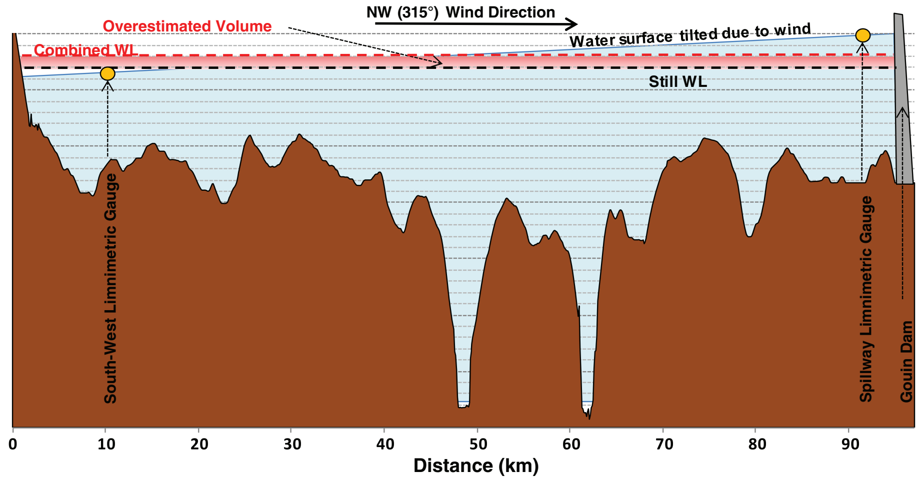

Fig. 1. (Color) Schematization of water-volume error induced by the effect of a northwestern wind at the Gouin Reservoir; WL = water level

directly and is deduced from the turbines' efficiency curves, the spillway capacity curve, the floodgates opening height, the alternator-measured power output, and the upstream and downstream water levels of the reservoir; ΔS = variation of water volume storage in the reservoir during a fixed time interval.

The WBE as solved by Hydro-Québec may seem simple at first glance. However, the calculation of each of its terms is complex because it relies on several equations and intermediate information (Haché et al. 1996). Therefore, the calculation of natural flow by WBE is subject to many sources of uncertainty originating from the computation (Q_{AV}, Q_{AM}, and ΔS).

As shown in Eqs. (2) and (3), the WBE depends on water-level measurements. At a daily scale, limnimetric gauges are greatly influenced by wind effect over the reservoir. In fact, wind setup and short-term seiches cause water-level fluctuations that are not originating from natural inflow (Croley 1987). These fluctuations affect the calculation of N_c from Eq. (2), thus leading to an error caused by wind effect in the ΔS term of the WBE. The concept of this type of error is schematized in Fig. 1 for the Gouin Reservoir in Quebec, Canada.

As shown in Fig. 1, the reservoir is equipped with two limnimetric gauges: the Southwest gauge and the gauge near the spillway dam. Both gauges are separated by approximately 100 km. Because of the reservoir shape, a wind originating from the Northwest is expected to increase significantly the water level near the spillway gauge while a slight decrease is expected at the Southwest gauge (Haché et al. 2003). Consequently, the resulting combined water level and the reservoir volume are overestimated compared with the still water level.

John et al. (1995), Simons and Schertzer (1989), and Schwab (1978) have all developed one- and/or two-dimensional (2D) numerical models to study how wind affects water levels from small to large lakes without getting into too much details of how it affects the WBE. Haché et al. (2003) used nonparametric regression modeling to relate wind conditions to water-level differences between the limnimetric gauges of large reservoirs without clearly quantifying the error introduced in the WBE. Furthermore, Croley (1987) studied the long-term wind setup errors in mean Erie and Superior Lake levels at a weekly to monthly time step. At these timescales, natural inflow errors from short-term setups, seiches, and tides are filtered out by the large time interval. However, because Hydro-Québec calculates daily WBE, wind errors in natural inflow have to be approximated at the same time step as the WBE is computed. The objective of this paper is to improve the understanding of the error in the natural inflow estimation caused by wind effects at a daily timescale where the short-term effects related to wind are not negligible. The unsteady- and steady-state modeling approaches are used for this purpose. The unsteady-state approach is deemed more realistic than steady-state modeling in the sense that it can consider reservoir seiching effects due to wind.

Description of the Case Study

Gouin is the head reservoir of the St. Maurice River's hydroelectric complex. With a water surface of more than 1,700 km^2, Gouin's purpose is to regulate flows and increase the potential energy of the St. Maurice River. The inspection of its bathymetric data has revealed that it is highly complex with the presence of many islands, tidal flats, narrow flow sections, etc. Accordingly, wind effect on the reservoir is expected to vary as the operating water level changes over time. Two water-level gauges and a wind-measurement station are installed on this reservoir. Their location is shown at Table 1 and Fig. 2 along with bathymetric data.

The available data for this study span from May 1, 2007, to July 1, 2012 and consist of the following:

- water level at the Southwest gauge and the spillway gauge at, respectively, 15- and 5-min intervals;
- combined water level calculated by Eq. (3) at the 5-min interval;
- spilled flow at hourly intervals;
- natural inflow calculated by Eq. (1) at daily intervals; and
- wind velocity and direction at hourly intervals.

The inspection of available data reveals that wind effect is perceived as noise in the natural inflow signal. Based on the dominant wind directions from Fig. 3, under constant steady winds, the water level near the spillway gauge is more likely to rise, whereas it is more likely to decrease near the Southwest gauge. This effect is illustrated in Fig. 4 with the appropriate data.

Table 1. Wind Station and Limnimetric Gauges Coordinates

		UTM coordinates zone 18 datum: GRS80/NAD83	
Gauge identifier	Description	Easting (m)	Northing (m)
Southwest gauge	Water-level gauge Meteorological gauge	475946	5366390
Spillway gauge	Water-level gauge	566875	5356670

Note: UTM = Universal Transverse Mercator.

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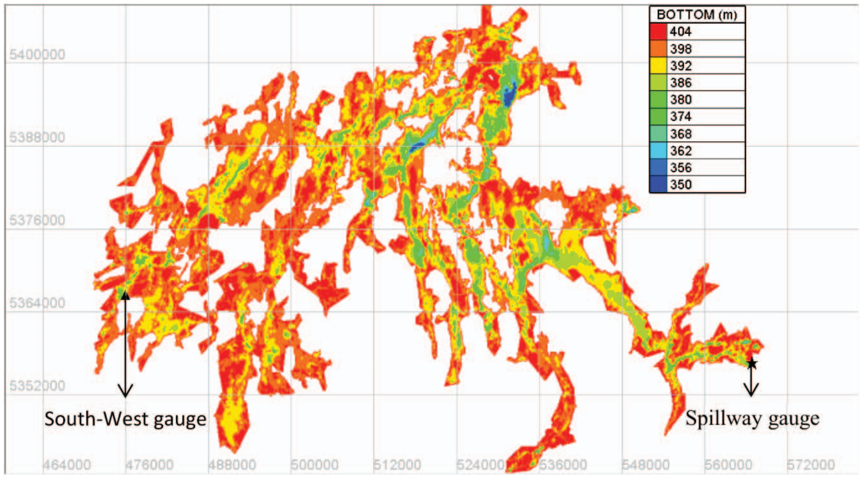

Fig. 2. (Color) Bathymetric data and gauge locations of the Gouin Reservoir; created from mesh generator *Blue Kenue* developed by the Canadian Hydraulics Centre (CHC)

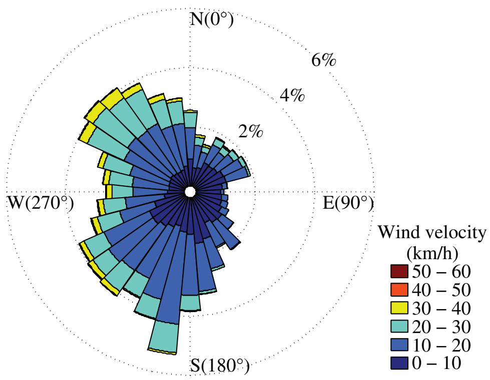

Fig. 3. (Color) Upwind direction data measurements expressed as wind rose for the Gouin Reservoir (data span from May 1, 2007 to July 5, 2012)

From May 2, 2007, to May 4, 2007, wind speed is minimal. During this interval, there is a slight 5-cm offset between the gauges, which could be related to water flowing across the reservoir. However, the water levels at the limnimetric gauges and also the combined water level do not vary significantly through time, and consequently, the WBE seems to provide a reasonable estimate of the natural inflow. Suddenly, a wind episode with a maximum velocity of 30 km/h occurs between May 4, 2007, and May 6, 2007. This short storm clearly tilts the water surface near the spillway gauge so that the combined water level varies abruptly. Consequently, the natural inflow signal calculated by WBE gets noisy during this sequence. Furthermore, it can be noticed that because the WBE is a calculation that is computed between two consecutive time steps, the error encountered on May 5, 2007, still affected the natural inflow signal on May 6, 2007, but with an inverse sign. Depending on the noise magnitude in the signal and the

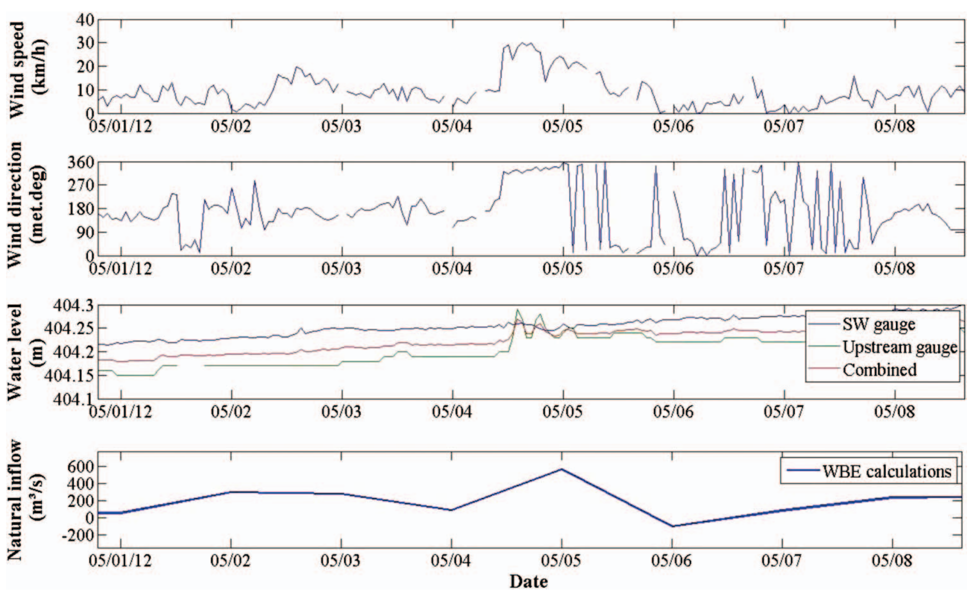

Fig. 4. (Color) Isolated noise in natural inflow signal calculated by Eq. (1) between May 4, 2012, and May 6, 2012, caused by wind effect on water-level measurements (Gouin Reservoir)

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wind conditions, it is sometimes needed to wait during a much longer period from weeks to months to determine or verify past natural inflow values at the Gouin Reservoir. Consequently, day-to-day reservoir management decisions are hindered because of this time-frame lag affecting the estimation of natural inflow by WBE.

In the following section, natural inflow error like the one shown in Fig. 4 will be analyzed using a hydrodynamic model.

Methodology

The errors in the WBE caused by wind effects are studied for two modeling techniques: unsteady state and steady state. For unsteady-state modeling, a calibrated hydrodynamic model is used to perform simulations in closed system with temporally variable wind as the only forcing. The resulting simulated water levels at each specific gauge are then used in a WBE computation to estimate the error caused by wind effect. 2D hydrodynamic modeling is appropriate for the case study because a full discretization of three-dimensional (3D) currents is not required.

Afterward, the same 2D hydrodynamic model is calibrated under steady-state assumption with uniform winds. According to this hypothesis, the natural inflow error is evaluated. Thereafter, the hydrodynamic model performance in steady state is compared with different wind drag coefficient formulation.

Finally, the implications of estimating daily natural inflow errors using steady-state assumptions as compared with using unsteady-state approach are discussed.

The methodology used during this study is depicted at Fig. 5 in a flowchart format and described in the following sections.

Unsteady-State Modeling

It is unlikely to have a constant wind speed over several days in a row. In fact, to accurately represent the effects of surface seiche, wind setup, and temporal variation of wind, it is preferable to model them by performing unsteady-flow simulations. The main objective

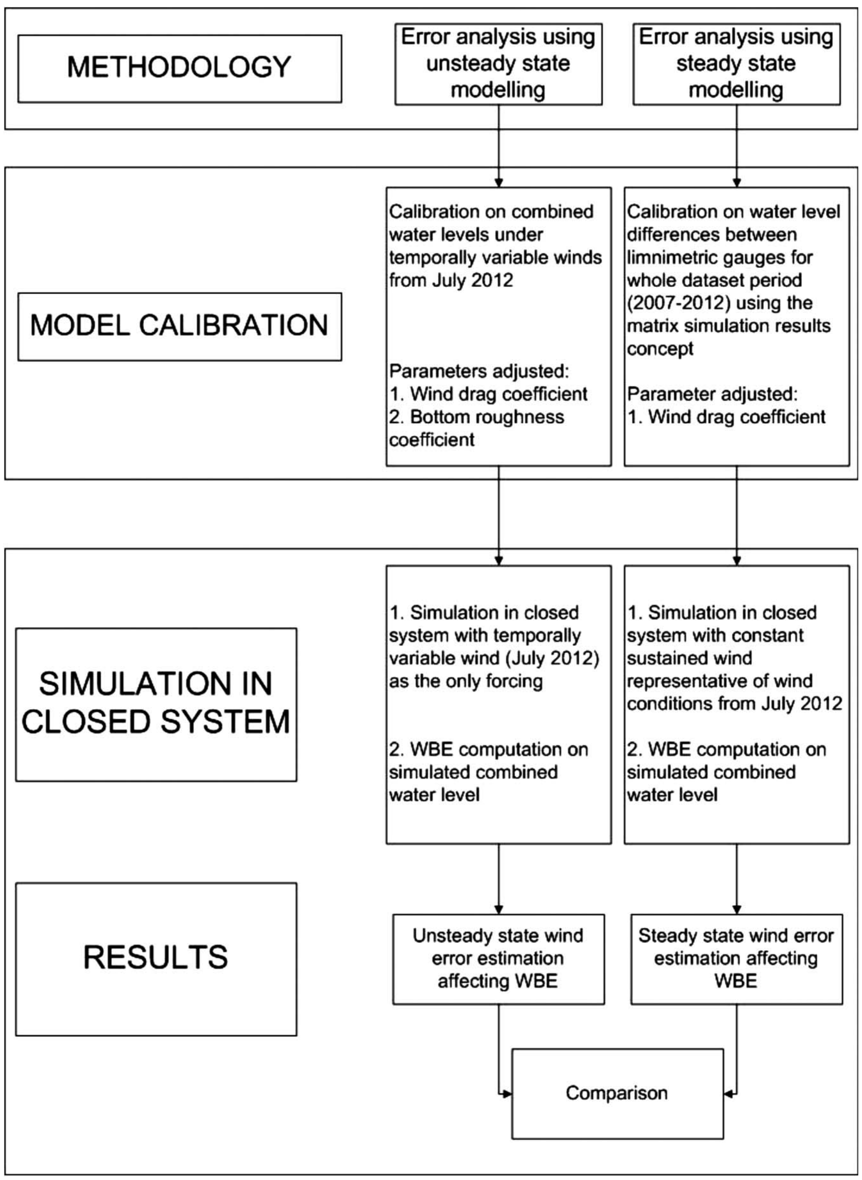

Fig. 5. Methodology in a flowchart format

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of this section is to perform, with the use of a calibrated 2D hydrodynamic model, unsteady-flow simulations affected by wind effects in a closed system. The first step for doing so is to calibrate the model. The calibration simulation is performed in an open system, meaning that it is driven by wind, outflows, and inflows. Preferably, for this application, the calibration should be performed during the low-flow period to minimize the effects of natural inflow errors. Once the model is calibrated, additional simulations in closed system can be performed. The closed system conditions allow for separating the effects of wind to study its impact on the reservoir, regardless of any other external sources that may affect the limnimetric gauges (i.e., evaporation, rainfall, groundwater flow). In other words, A_n, Q_{AV}, and Q_{AM} from Eq. (1) are neglected. Throughout the simulation, the water volume is maintained, as there is no inflow and outflow. However, the wind deforms the water surface and water-level variations occur at the limnimetric gauge location. Depending on the position of the instruments and the combination method C from Eq. (3), a water volume error can be introduced into the ΔS term from the WBE shown at Eq. (1). By applying the combination method of arithmetic weighting on the simulated water levels obtained by unsteady-flow simulations in a closed system, it is possible to make a preliminary diagnosis for the Gouin Reservoir to estimate the error range in the WBE due to wind effect.

To perform the previously described simulations, the *TELEMAC-2D* model developed by Électricité de France (EDF) in collaboration with Laboratoire National d'Hydraulique et d'Environnement (LNHE) is chosen for the availability of its source code. The function of wind forcing in this code is given by the following formulation (Hervouet 2007):

$$F_x = \frac{1}{h}\frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{water}}} C_D V_x \sqrt{V_x^2 + V_y^2} \tag{4}$$

$$F_y = \frac{1}{h}\frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{water}}} C_D V_y \sqrt{V_x^2 + V_y^2} \tag{5}$$

As can be deduced from Eqs. (4) and (5), the wind stress on water surface is dependent on the operating water level of the reservoir. This particularity will be explored in more detail in the next section about the steady-state modeling approach.

First, the mesh for *TELEMAC-2D* was developed using 223,000 calculation nodes with constant triangular elements of 100 m. The mesh resolution and element size were determined by a prior sensitivity analysis. The purpose of this sensitivity analysis was to select the best trade-off between computation time and model result accuracy.

The model calibration for unsteady-state simulations has been performed by adjusting the wind drag coefficient C_D and the Manning friction coefficient. As mentioned earlier, the calibration simulation is performed using an open system. The calibration's goal is to try to reproduce the observed combined water level N_c during a month containing many strong wind episodes. The calibration was focused on reproducing N_c instead of the water levels at the two limnimetric gauges, because N_c is directly related to the wind-induced error in the ΔS term from Eq. (2). In other words, if N_c is not reasonably reproduced by the model, the wind-induced errors affecting the WBE are not likely to be assessed correctly. Furthermore, minimizing the errors at both individual gauges by varying the calibration parameters may lead to a process requiring the selection of a trade-off between the model representativeness at both gauges which will not necessarily minimize the errors in the simulated N_c. The month that was chosen to have the calibration perform was July 2012 because as shown in Fig. 6, it was found to contain multiple wind episodes with peak speeds higher than 30 km/h. Furthermore, the low-flow period of the Gouin Reservoir would occur in this month. This meant that lower natural inflows would ensure that managing their uncertainty was less likely to affect the calibration process. In fact, the natural inflows obtained with the WBE for the month of July 2012 are oscillating around 0 m^3/s. Thus, as shown in Fig. 6, inflows to the model were assumed to be negligible during that period. The calibration simulation is then driven by outflows and wind effect only.

The best simulation representation was obtained using a wind drag coefficient of 3.7×10^{-3} and a Manning coefficient of 0.018. The calibration results for these parameters are presented in Fig. 7 and are compared with a no wind simulation.

As shown in Fig. 7, the calibration simulation including wind effect performs better and is more responsive than the simulation without it. The model negative bias is explained under the assumption that the natural inflow was assumed null, but realistically speaking, there was probably the existence of low natural in-

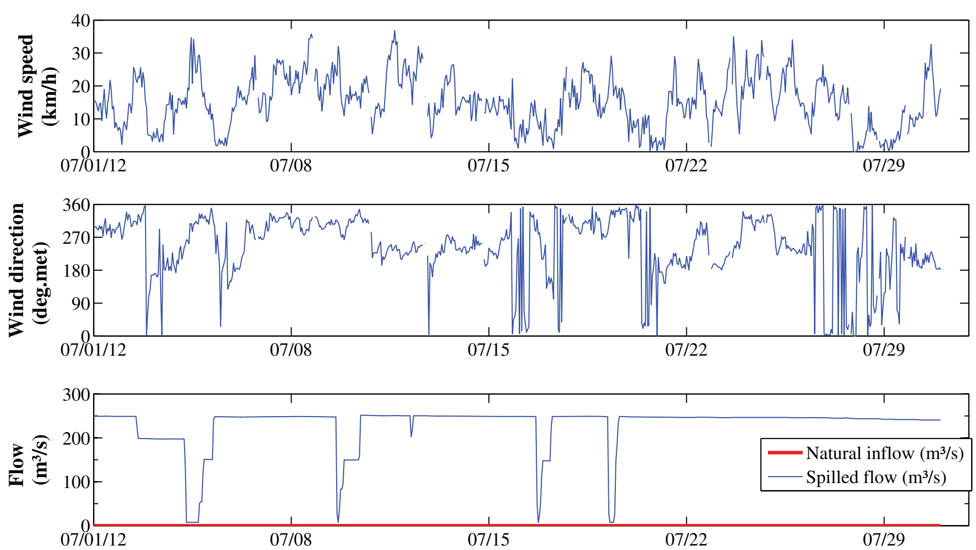

Fig. 6. (Color) Forcing data of the month of July 2012 for the calibration simulations (open system)

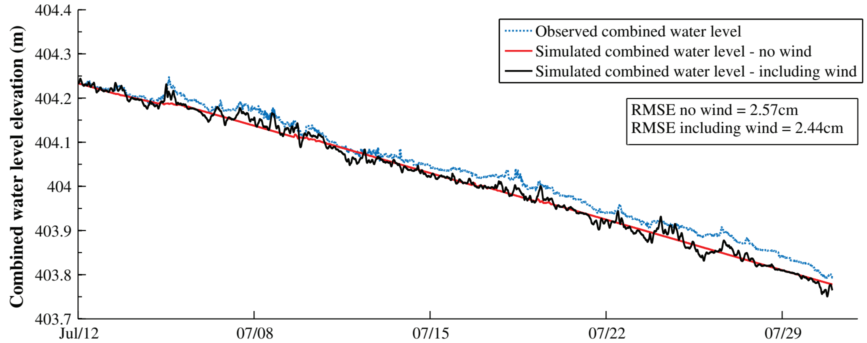

Fig. 7. (Color) Best calibration simulation of the month of July 2012 in an open system

flow. As mentioned earlier, the calculated daily natural inflow for this period, while oscillating around 0 m^3/s over the month of July 2012, cannot be verified as its signal is deemed too noisy. This fact makes the calibration process challenging and outlines the importance of selecting a low-flow period for the calibration. Ultimately, a relatively high constant wind drag coefficient (3.7×10^{-3}) was selected to increase the model representativeness during the highest wind episodes. However, when wind speed is lower, the simulated N_c may appear noisy because of the higher wind drag coefficient. In fact, the numerical model does not reproduce exactly the observed N_c at each time step. Consequently, this will affect the assessment of wind-induced error when the model is run in a closed system. However, the combined water levels are reproduced reasonably well enough to obtain a reasonable estimation of the maximal wind-induced error range that occurred during the month of July 2012 for the Gouin Reservoir.

Steady-State Modeling

Steady-state hypothesis consists of the assumption that the flow characteristics (water depth and velocity) are stabilized and do not vary over time. In the context of this section, this hypothesis is to expect that the water surface is instantly tilted toward downwind direction depending on wind velocity and direction (Simons and Schertzer 1989). The main disadvantage associated with this assumption is that the water-surface inertia cannot be considered (seiche and inertial forces). However, its advantage is that the modeling and the simulation of wind setup do not require the model to run continuously, as is the case with unsteady-flow modeling. In fact, the steady-state wind setup modeling only needs to be performed once, as long as it covers all the conditions and wind characteristics that can be observed at the study site. Consequently, this type of approach could be more easily established for operational use to correct or estimate wind-induced natural inflow error. By operational use, it is implied that the process of calculating WBE wind-induced error would be performed every day. Steady-state modeling will be experimented on to simulate wind setup over the Gouin Reservoir. Afterward, different wind drag coefficient formulations will be compared during the model calibration. Finally, the hydrodynamic modeling will be used in steady state and the natural inflow's wind errors will be estimated under this assumption in the same fashion as is done with the unsteady-state simulations.

Prior to estimating natural inflow's wind errors, it is necessary to calibrate the hydrodynamic model according to the steady-state assumption. To this end, the steady-state calibration is performed by searching the best wind drag coefficient for different classes of wind velocity, wind direction, and operating water level. A prior sensitivity analysis has revealed that the Manning coefficient does not affect the simulated water level when the steady-state conditions are reached under constant wind forcing. The performance of the calibration simulations is evaluated by calculating the root-mean-square error (RMSE) of the simulated versus observed water-level differences between gauges for all the available data discussed in the "Description of the Case Study" section. The water-level differences are defined by (Haché et al. 2003)

$$\Delta H_{ij,t} = L_{i,t} - L_{j,t} \tag{6}$$

However, the formulation of water-level differences given by Eq. (6) contains a signal proportion caused by wind effects and another signal proportion that is caused by the water flow in the reservoir. To use the formulation of Eq. (6) as a performance indicator to model steady flow under sustained winds, it is necessary to remove the signal proportion originating from the water flow in the reservoir (Haché et al. 2003). To perform this step, the signal obtained by Eq. (6) is averaged over a moving window of 15 days. The averaged signal corresponds to the water-level differences without the short-term effects of wind. The water-level differences from Eq. (6) are then subtracted to the averaged signal to obtain the water-level differences only influenced by the wind. The described procedure to obtain the reference water-level differences data set for the calibration is illustrated in Fig. 8. It is interesting to note that during the period that is shown, the water-level differences due to the flow of water in the reservoir vary between 0 m during the low-flow period to 0.1 m during the spring flood.

Once the reference data set has been obtained, the calibration simulations can be performed. A simulation is implemented by forcing the model with a constant and uniform wind. Then, the results are extracted at the last time step when the simulated levels are stabilized and no longer vary through time (steady state). The calibration phase in steady state consists of a multiple series of simulations forced by constant and uniform wind that would cover wind speeds of 5–30 km/h in four directions, 0°, 90°, 180°, and 270°, and at seven different operating levels, 400, 400.85, 401.69, 402.54, 403.39, 404.23, and 405.08 m. There are just as much sets of simulations needed to cover each of the following wind drag coefficients: 0.5×10^{-3}, 0.7×10^{-3}, 1.0×10^{-3}, 1.2×10^{-3}, 1.4×10^{-3}, 1.8×10^{-3}, 2.7×10^{-3}, 3.7×10^{-3}, 4.7×10^{-3}, 5.7×10^{-3}, and 6.7×10^{-3}. In total, 1,848 *TELEMAC-2D* simulations ($11 C_D \times 7$ water levels $\times 6$ wind velocities $\times 4$ directions) have been performed to calibrate the Gouin model in steady state. These results are then organized in a 3D matrix, where each dimension corresponds, respectively, to the water-level range, the wind-velocity range, and the wind direction range. An example of this 3D matrix for a given C_D is shown in Fig. 9.

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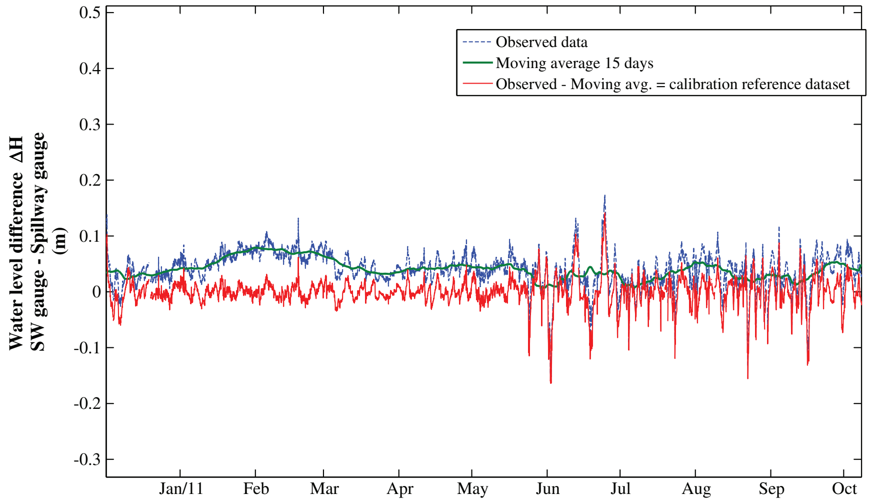

Fig. 8. (Color) Procedure to obtain the reference data set of water-level differences for steady-state model calibration; SW = Southwest

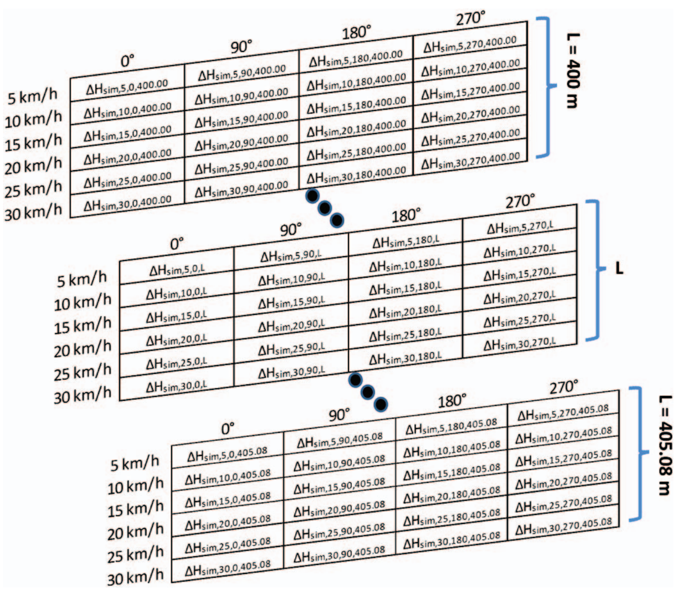

Fig. 9. (Color) Example of three-dimensional matrix simulation results for a given wind drag coefficient

Because the direction variable was discretized every 90°, to obtain a result for each direction, the following trigonometric composition was used (Croley 1987):

If $0° \leq \theta \leq 90°$

$$\Delta H_{\text{sim},\theta} = \Delta H_{\text{sim},90°} \sin\theta + \Delta H_{\text{sim},0°} \cos\theta \tag{7}$$

If $90° < \theta \leq 180°$

$$\Delta H_{\text{sim},\theta} = \Delta H_{\text{sim},90°} \sin\theta + \Delta H_{\text{sim},180°} \cos\theta \tag{8}$$

If $180° < \theta \leq 270°$

$$\Delta H_{\text{sim},\theta} = \Delta H_{\text{sim},270°} \sin\theta + \Delta H_{\text{sim},180°} \cos\theta \tag{9}$$

If $270° < \theta \leq 0°$

$$\Delta H_{\text{sim},\theta} = \Delta H_{\text{sim},270°} \sin\theta + \Delta H_{\text{sim},0°} \cos\theta \tag{10}$$

Afterward, to obtain a result for each observed operating water level, wind speed, and wind direction, a 3D linear interpolation is built between the different ΔH_{sim} values, which are organized in the 3D matrix solutions shown in Fig. 9. It is important to note that once the matrix is obtained, the interpolation process resolves in few seconds with today's computing technology. Hence, generating a daily ΔH_{sim} time series for the entire data record (2007–2012) is extremely fast. The interpolation process is appropriate to implement for operational use as it does not require any intensive CPU computations unlike the unsteady-state approach where the hydrodynamic model would need to run continuously.

To complete the calibration process, the selection of the best wind drag coefficient for each discretized wind velocity and direction must be performed. To do so, simulated and observed water-level differences between the Gouin Reservoir limnimetric gauges are compared by using the RMSE indicator. The best wind drag for each wind speed and direction category is selected by choosing the one that gives the lowest RMSE value. The best wind drag for each wind speed and direction is presented in Table 2.

Based on Table 2, the overall best wind drag coefficient is 1.0×10^{-3} (5th column of Table 2). However, it is possible to note that the wind drag coefficient greatly varies depending on wind speed and direction. First, when the drag coefficient is function of wind speed (4th column of Table 2), it is noted that for very low wind speeds, a high drag coefficient gives the best results (3.7×10^{-3} for 5 km/h and 2.8×10^{-3} for 10 km/h). At higher wind velocities, the wind drag coefficient stabilizes at 1×10^{-3}.

When the wind drag coefficient is considered variable as a function of both wind velocity and direction (3rd column of Table 2), its value is almost constant for direction 0° and 270° (1.4×10^{-3} and 1.0×10^{-3}, respectively). The 90° axis is the most sensitive of all directions: the wind drag coefficient varies from 5.7×10^{-3} for 5 km/h to 1.8×10^{-3} for 30 km/h wind velocities. Finally, the drag coefficient for direction 180° is very high for lower wind speeds (5 and 10 km/h) and very low for higher wind speeds (>20 km/h).

Furthermore, based on all the carried simulations, the performance of the hydrodynamic model in steady state can be analyzed for different wind drag formulations. The wind drag coefficient can be considered constant or variable as a function of wind speed and/or direction by using the results presented in Table 2. In addition, it is possible to verify if the effects of a variable operating water level

Table 2. Calibration Results: Best Wind Drag Coefficient according to Different Formulations

Wind velocity (km/h)	Wind direction (deg. met)	C_D for varying wind velocity/direction (10^{-3})	C_D for varying wind velocity (10^{-3})	Overall best C_D (10^{-3})
5	0	1.4	3.7	1.0
	90	5.7		
	180	4.7		
	270	0.5		
10	0	1.4	2.8	
	90	5.7		
	180	2.8		
	270	1.0		
15	0	1.4	1.2	
	90	2.8		
	180	1.0		
	270	1.0		
20	0	1.4	1.0	
	90	2.8		
	180	0.5		
	270	1.0		
25	0	1.4	1.0	
	90	1.8		
	180	0.5		
	270	1.0		
30	0	1.4	1.0	
	90	1.8		
	180	0.5		
	270	1.0		

Note: deg. met = meteorological degree.

described by Eqs. (4) and (5) increase the performance of the steady-state modeling. More precisely, when the effects of a variable operating water level are taken into account, a linear 3D interpolation is processed in the matrix simulation results shown in Fig. 9. By contrast, when the effects of variable operating water level are neglected, a 2D interpolation is performed on the wind velocity and direction while the operating water level is fixed as a constant and equal to the mean combined water level of the whole available data set. The performances of different steady-state modeling techniques are presented in Table 3.

Based on Table 3, the steady-state modeling of each C_D formulation behaves better than when assuming that the wind has no effect on the water surface. The best steady-state approach is obtained by taking into account a variable operating water level with a variable wind drag coefficient as a function of wind speed and wind direction. Using a variable operating water level gives a slightly better performance for high wind velocity. For lower wind velocity, the performance gain is barely noticeable. Furthermore, this approach requires the most simulations to construct the matrix simulation results. As will be discussed in the "Results and Discussion" section, simpler C_D formulation may lead to the same estimation of natural inflow error.

Results and Discussion

Unsteady-State Modeling

Once the model is calibrated in the unsteady state as an open system (Fig. 7), the same month (July 2012) is simulated again in the closed system with wind as the only forcing. The natural inflow's wind errors are then evaluated with the simulated water levels. First, Eq. (2) is used to calculate the simulated N_c. Then, Eq. (3) is used to calculate the ΔS term. Because there are no inflows and outflows in the closed system, the ΔS term from Eq. (1) equals to the natural inflow's error caused by wind effects. The results of the closed system simulation are shown in Fig. 10.

As shown in Fig. 10, the wind effects on the Gouin Reservoir have an extremely important impact on the natural inflow calculation by WBE. The wind affects the calculation of N_c by a few centimeters. However, by converting this error measured in centimeters to an error in cubic meter per second (m^3/s), its maximal magnitude estimated by unsteady simulation in the closed system is $-340\ m^3/s$ during the month of July 2012. As outlined in Fig. 10, the error due to wind in the natural inflow calculation by WBE occurs every day of the simulation regardless of wind velocity or direction. Therefore, a significant and continuous natural inflow error is expected over the duration of the historical data. Finally, the natural inflow's error sign (+ or −) does not seem related to the wind direction. This may be explained by the inertial forces acting on the water surface when the wind speed or direction changes abruptly. As a result, an oscillatory motion of the water surface (seiche) is triggered and continues until the equilibrium return. Depending on the duration to the equilibrium return, the inertial forces may add an additional error in the calculation of natural inflow.

Steady-State Modeling

The natural inflow error estimations of the simplest and the more complex C_D formulation are presented in Tables 4 and 5. Wind

Table 3. Performance of Steady-State Modeling Approach Using Different Wind Drag Formulations

C_D formulation	No wind	Constant C_D	C_D varying with wind velocity	C_D varying with wind velocity/direction	C_D varying wind with velocity/direction/water level
Dimension of matrix results	0	2	2	2	3
Minimum number of simulations[a]	0	24	96	168	1,848
Wind velocity (km/h)			RMSE ΔH_{sim} versus ΔH_{obs} (cm)		
5	2.68	2.57	2.45	2.25	2.25
10	3.33	3.09	2.95	2.66	2.66
15	3.61	3.24	3.23	3.00	2.99
20	4.14	3.39	3.39	3.33	3.32
25	5.02	3.78	3.78	3.81	3.79
30	6.42	4.51	4.51	4.53	4.49
Global	3.86	3.25	3.21	3.06	3.05

Note: Only best C_D formulations are presented based on hydrodynamic results.
[a]Minimum number of simulations required to build the matrix simulation results.

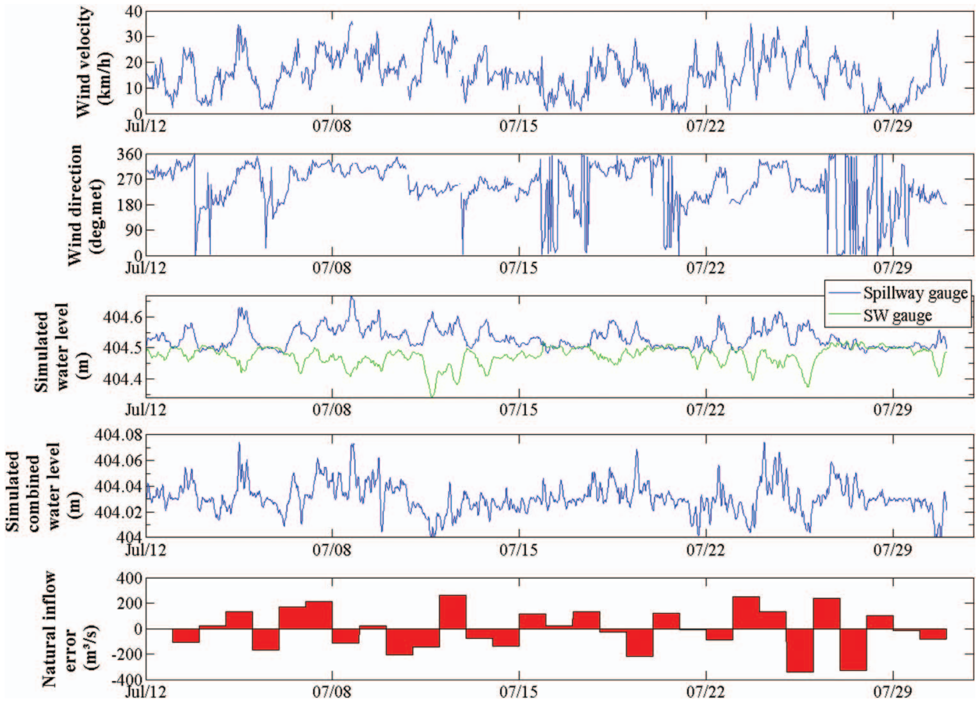

Fig. 10. (Color) Unsteady-flow simulation of the month of July 2012 allowing the estimation of the natural inflow's wind error; SW = Southwest

Table 4. Steady-State Hydrodynamic Results of the Effects of Wind on Gouin Reservoir Leading to the Highest Natural Inflow Error by Considering a Constant C_D

Model result	From Fig. 11(a)	From Fig. 11(b)	From Fig. 11(c)
Initial water level (m)	404.5	404.5	404.5
Wind velocity (km/h)	26	26	26
Wind direction (degree)	180	0	315
C_D	1×10^{-3}	1×10^{-3}	1×10^{-3}
ΔH_{sim} (cm)	0.2	−0.1	−4.1
Southwest gauge response (cm)	−0.6	0.6	−1.5
Spillway gauge response (cm)	−0.8	0.7	2.6
Combined response (cm)	−0.7	0.65	0.55
Volume variation error (hm^3)	−12	11	9
Daily natural inflow error (m^3/s)	−134	124	105

Table 5. Steady-State Hydrodynamic Results of the Effects of Wind on Gouin Reservoir Leading to the Highest Natural Inflow Error by Considering a Variable C_D as a Function of Wind Velocity and Direction

Model result	From Fig. 12(a)	From Fig. 12(b)	From Fig. 12(c)
Initial water level (m)	404.5	404.5	404.5
Wind velocity (km/h)	26	26	26
Wind direction (degree)	135	0	315
C_D	1.8×10^{-3}	1.4×10^{-3}	1×10^{-3}
ΔH_{sim} (cm)	7.5	−0.2	−4.1
Southwest gauge response (cm)	2.8	0.8	−1.5
Spillway gauge response (cm)	−4.7	1.0	2.6
Combined response (cm)	−0.95	0.9	0.55
Volume variation error (hm^3)	−16	15	9
Daily natural inflow error (m^3/s)	−181	172	105

velocity was fixed to 26 km/h. This value corresponds to the daily average maximal wind velocity that occurred during July 2012, which is the same period that was simulated with the unsteady-state approach. By referring to the wind rose in Fig. 3, a wind velocity of the same magnitude (26 km/h) occurs rather often. Additional steady-state simulations were carried out to cover the Northeast, Southeast, Southwest, and Northwest wind directions. The best wind drag coefficients from Table 2 were used for each of these additional directions and fixed velocities. To estimate the natural inflow error caused by wind, the free surface elevations computed at the closest node of the mesh from each limnimetric gauge have been extracted. Based on these simulated water levels, the WBE is computed by calculating the ΔS term for each direction for a fixed wind velocity. As can be seen in Tables 4 and 5, a horizontal water surface was assumed as the initial condition for the simulations and for the WBE error calculations with Eq. (3). Consequently, this assumption will maximize the wind effects on the WBE in cases of a very long wind episode with constant direction because, in reality, the water surface may remain tilted between two consecutive time steps. In that particular case, the simulated error will be higher than the actual wind setup error affecting the WBE. For using the steady-state modeling approach for day-to-day operational use with more precision, it would then be preferable to take into account the simulated results from the previous time step instead of assuming a horizontal water surface.

The steady-state hydrodynamic results leading to the highest natural inflow error by considering a constant C_D are presented in Table 4. This formulation of C_D is the most simple to use but has led to a lower performance based on the results presented in Table 3. On the left side of Table 4 are presented the hydrodynamic results and on the right side are presented important variables and numeric values that allow the calculation of the natural inflow error. From Table 4, the critical wind directions leading to the highest natural inflow error are 180°, 0°, and 315°. The highest error magnitude is -134 m^3/s at a wind direction of 180°.

By contrast, the steady-state hydrodynamic results leading to the highest natural inflow error by considering a variable C_D are presented in Table 5. Unlike the constant C_D formulation, the variable C_D formulation has a better performance compared with observed data but requires much more steady-state simulations for the calibration of the model. The natural inflow errors estimated by this

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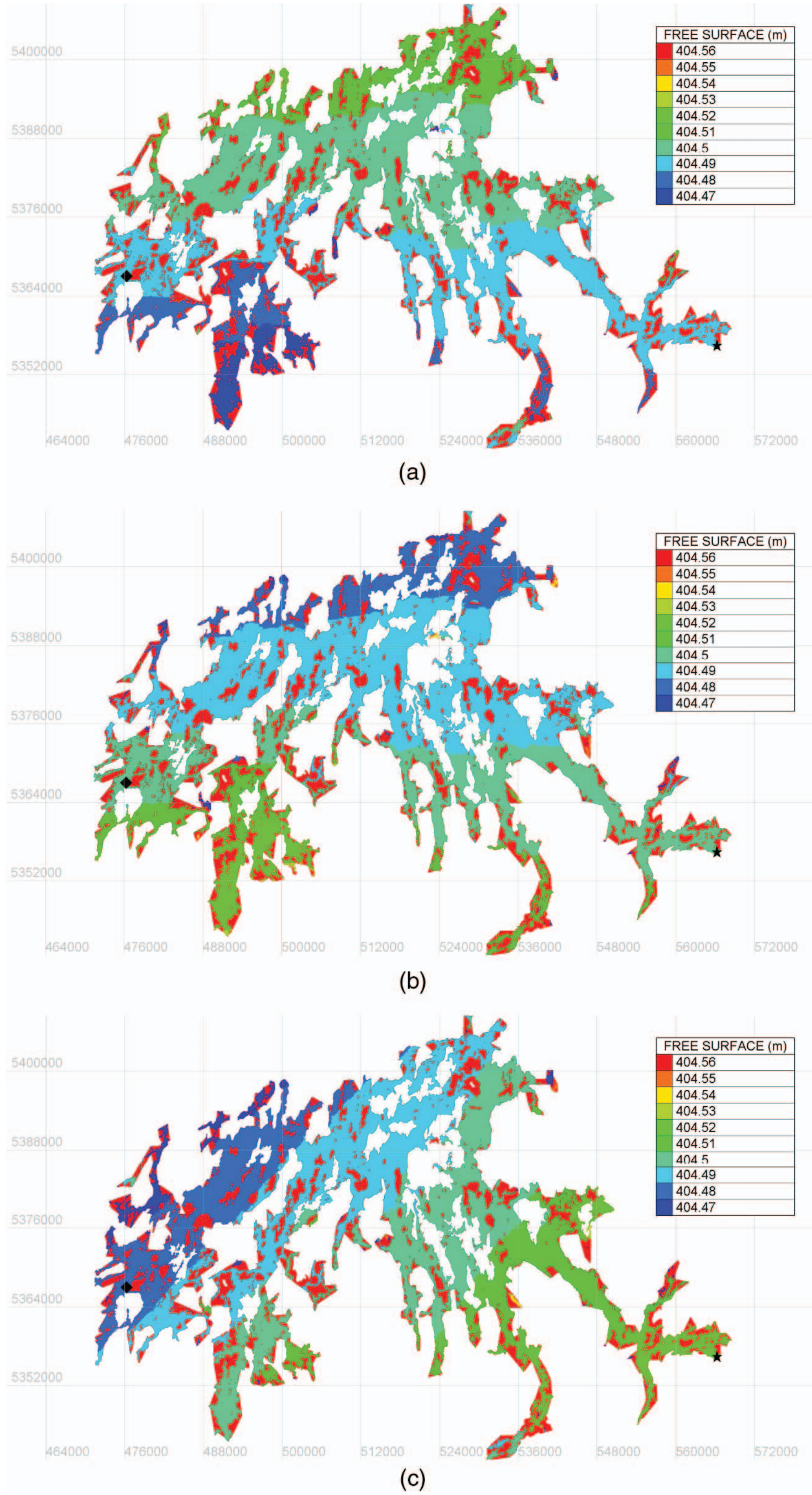

Fig. 11. (Color) Steady-state hydrodynamic results of water-surface elevation by considering a constant C_D: (a) wind direction = 180°; (b) wind direction = 0°; (c) wind direction = 315°

C_D formulation are therefore expected to be more reliable than those estimated by the constant C_D formulation. From Table 5, the critical wind directions leading to the highest natural inflow error are 135°, 0°, and 315°. The magnitude of the highest error is estimated at $-181\ \mathrm{m^3/s}$ for a wind direction of 135°.

Finally, by analyzing the results from Tables 4 and 5, it can be concluded that the magnitude of the natural inflow error is poorly related to ΔH_{sim}. In fact, the error magnitude is much more related to the combined responses. Furthermore, for every steady-state results presented in Tables 4 and 5, the wind response at the spillway gauge is always higher than the response at the Southwest gauge. For an arithmetic gauge weighting technique, which is used by Hydro-Québec, the combined response is calculated by averaging the responses of the Southwest and spillway gauges.

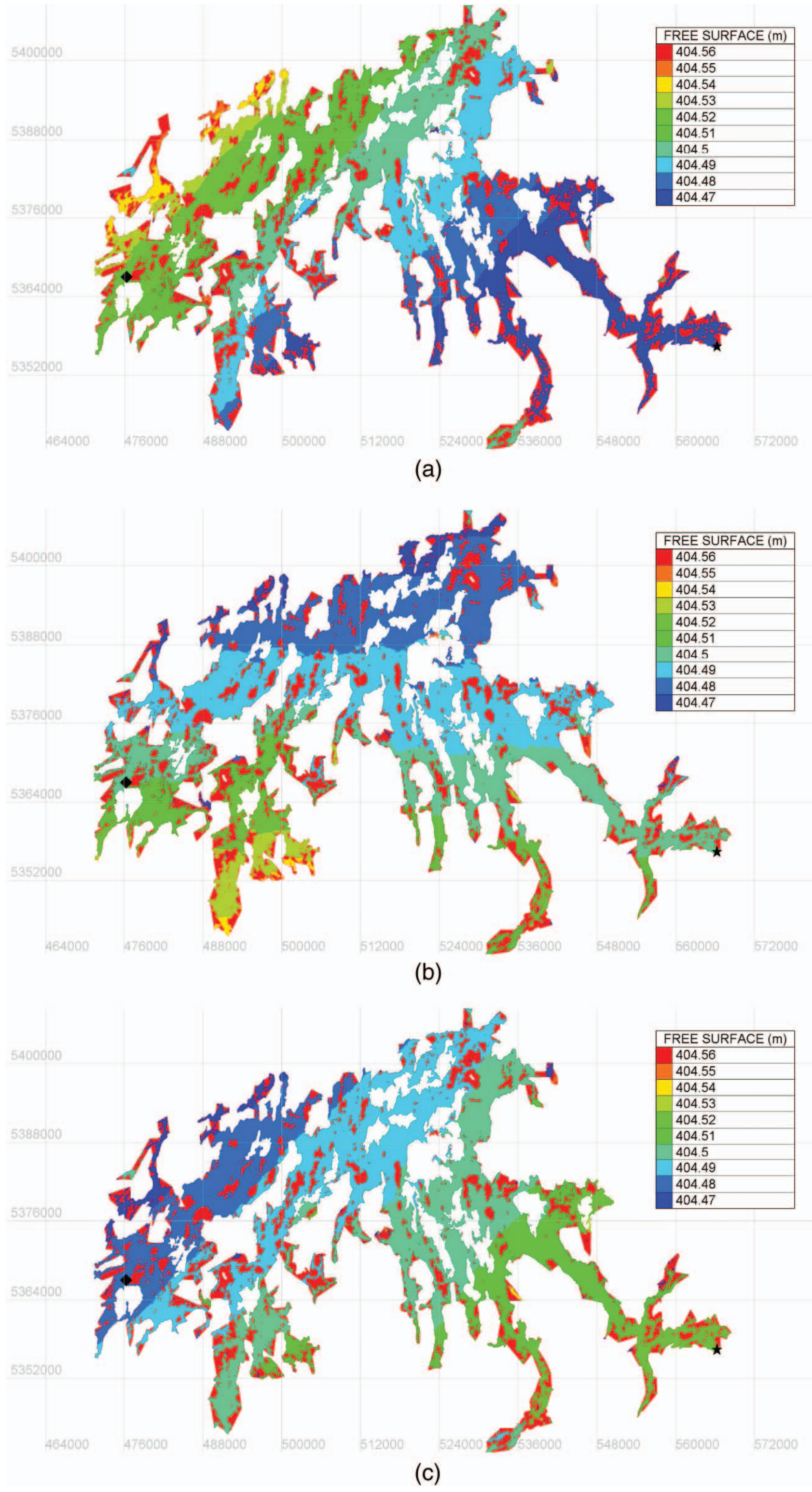

Fig. 12. (Color) Steady-state hydrodynamic results of water-surface elevation by considering a variable C_D as a function of wind velocity and direction; (a) wind direction = 135°; (b) wind direction = 0°; (c) wind direction = 315°

Because wind affects both limnimetric gauges differently, the use of an alternate gauge weighting technique could lead to a lower natural inflow error. For example, based on the simulation results, a less noisy natural inflow signal would be expected by lowering the weight of the spillway gauge and increasing the weight of the Southwest gauge when the wind is blowing in a 135°/315° axis. However, when wind is blowing in a 0°/180° axis, the wind error cannot be cancelled because the responses at both water-level gauges are of the same sign. In that case, it would be preferable to only consider the Southwest gauge for the weighting algorithm because this gauge is less influenced by wind effects than the spillway gauge.

Table 6. Description and Comparison of the Modeling Approaches Used to Estimate the Natural Inflow Errors Caused by Wind Effects

Modeling approach	Steady state		Unsteady state
C_D formulation	Constant	Variable	Constant
Minimum number of simulations required to evaluate the impacts of wind	44 ($4\theta \times 11C_D$)	1,848 ($6V \times 4\theta \times 7L \times 11C_D$)	Model running continuously during the required time frame
Effects of variable operating water level taken into account	No	Yes	Yes
Calibration on whole data set	Yes	Yes	Only July 2012
Maximum estimated daily natural inflow error magnitude caused by wind during the month of July 2012 (m^3/s)	−134	−181	−340
Critical wind direction	180°	135°	No precise correlation found with direction because of seiche effects
Advantages	Simple	Higher calibration performance for steady-state assumption	Considering inertial effects and wind duration effects
Disadvantages	Low calibration performance; only wind setup is considered	Only wind setup is considered	Hardly applicable for operational use to estimate natural inflow error

Conclusions and Recommendation

With the aid of hydrodynamic simulations, the natural inflow maximal error range caused by wind effects has been estimated by unsteady-state and steady-state modeling approaches for the month of July 2012 of the Gouin Reservoir. These approaches are summarized in Table 6.

From Table 6, for steady-state modeling, different C_D formulations were tested. The formulation giving the best calibration performance is the one determining a variable C_D as a function of wind velocity/direction and by taking into account the effects of a variable operating water level. The maximum natural inflow error that was estimated for a steady-state modeling with a variable C_D formulation is $-181\ m^3/s$. The simpler constant C_D formulation combined with a constant operating water level did give a maximum error magnitude in the same range of a variable C_D formulation ($-134\ m^3/s$) despite its lower calibration performance. However, the critical directions leading to the highest natural inflow errors were not the same. Ideally, for optimal model performance in steady state, a C_D coefficient varying with direction is required. This goes in accordance with the conclusions found by Simons and Schertzer (1989) with their analysis of wind setup between two limnimetric gauges on Lake St. Clair. In the case of unsteady-state modeling, wind direction did not seem to correlate with the error sign (+ or –) as possibly related to seiches effects. This observation supports the conclusion that for relatively constant wind events around midnight (time of the day for which the WBE is computed), the steady-state approximation and the concept of critical direction are valid. However, for wind events where direction and/or velocity change abruptly, the error sign will not necessarily be properly estimated with a steady-state assumption. The difference between the daily natural inflow maximal error estimated during the month of July 2012 by steady-state modeling (-134 and $-181\ m^3/s$) and the maximum error estimated by unsteady-state modeling ($-340\ m^3/s$) is very high. This can be explained by the following reasons:

- The inertial effects and wind setup buildup duration effects that are not taken into account in the steady-state modeling; and
- The fact that the wind velocity was averaged over a daily period to estimate the daily natural inflow error for the steady-state modeling.

The effect of averaging the wind velocity lowers the measured instantaneous velocity peaks. This has the effect of lowering the estimation of natural inflow errors. For these reasons, the unsteady-state modeling may be more appropriate. In other words, if wind setup is solely considered (steady-state assumption) wind-induced errors in the WBE may be underestimated.

However, developing an unsteady-state model for multiple hydroelectric reservoirs to simulate the natural inflow errors caused by wind effects for operational use could be quite time and resources consuming. It then becomes relevant to consider using steady-state models to develop a methodology relevant for operational use to correct the effects of wind on the WBE that would be simultaneously applicable to multiple hydroelectric facilities. As such, on reservoirs with long time series of water level and wind data, statistical regressive approach as discussed by Haché et al. (2003) could be employed to evaluate and/or correct the wind errors in the WBE. By contrast, on reservoirs with limited wind data time series, steady-state hydrodynamic modeling could be used. Furthermore, during complex wind events where important seiches could be expected, short-term unsteady-state simulations could be utilized in support to validate and confirm the wind error estimated by the steady-state model. It is also important to note that with the use of hydrodynamic models, it was found that wind errors correlated more with the responses at each limnimetric gauge rather than with the water-level differences (ΔH) between the gauges. The nonparametric regression developed by Haché et al. (2003) could then be updated using the wind-induced responses at each gauge instead of ΔH between the gauges. The regressions could also benefit from adding a varying operating water level because it was found to increase the performance of the steady-state simulations.

Croley (1987) evaluated a limnimetric gauge weighting to minimize long-term wind setup errors at a weekly to monthly time step, which was too large for the needs of this specific study. In fact, a methodology to evaluate the wind errors valid for operational use has not yet been implemented for a short-term daily WBE. This paper has described and compared modeling approaches that could be used in such a methodology. However, for further study of wind-induced errors in the WBE using hydrodynamic modeling, it is recommended to increase calibration performance of both unsteady- and steady-state methods. For unsteady-state modeling, the calibration time frame would need to be increased, and drag coefficient could be adjusted for different directions to further optimize the performance of the model. For steady-state modeling, more wind directions could be simulated and included in the matrix simulation results so that linear interpolation could be used between the different wind directions instead of interpolating using the

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relation given by Eq. (7). Furthermore, the correction of short-term wind effects error in natural inflow estimation is not well-documented today in any form of literature, which may prove to be problematic. The main contribution of this study resides in the fact that modeling procedures, from model calibration to short-term WBE wind errors estimation, were established for an unsteady- and steady-state approach. One of the main limitations of the steady approach is the modeling of the seiches until the return of the reservoir to its original balance state. For future studies, the steady-state approach could benefit from an additional implementation to effectively estimate seiche effects on WBE in a nontransient fashion. For example, in addition to establishing relations between wind velocity/direction and wind setup, relations between wind velocity/direction gradient and water-level response could be subjects of experimentation. Observing how wind gradient affects both limnimetric gauges would help to understand the reservoir behavior when wind forcing abruptly changes near midnight during a WBE computation. The concept of matrix solution could be extended at more than three dimensions by including additional dimensions such as wind-velocity gradient, wind direction gradient, and water-level response at both limnimetric gauges at different time until the reservoir returns at an equilibrium water level.

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Notation

The following symbols are used in this paper:

C = water-level variations combination method [this function generally consists of assigning a weight at each water-level gauge; Hydro-Québec currently uses an arithmetic mean weighting attribution so that $C = (1/n)$];

C_D = wind drag coefficient;

F_{storage} = reservoir's storage curve, which allows the conversion of combined water level to water volume;

F_x and F_y = wind efforts transmitted in the momentum equation;

h = water depth;

L = water level recorded from limnimetric gauge on the reservoir of interest at midnight of day t;

N_c = combined water level corresponding to a representation of the mean horizontal water level of the reservoir of interest;

n = number of limnimetric gauges at the reservoir of interest;

V = water volume stored in the reservoir of interest;

V_x and V_y = perpendicular wind-velocity components;

$\Delta H_{ij,t}$ = water-level differences between gauges i and j during time t;

$\Delta H_{\text{sim},0°}$, $\Delta H_{\text{sim},90°}$, $\Delta H_{\text{sim},180°}$, and $\Delta H_{\text{sim},270°}$ = simulated water-level difference obtained directly from a *TELEMAC* simulation;

$\Delta H_{\text{sim},\theta}$ = simulated water-level difference between the Southwest and upstream gauges under sustained wind of direction θ;

θ = wind direction; and

ρ_{air} and ρ_{water} = air and water densities, respectively.

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