Interactive comment on "Representation of Water Management in Hydrological and Land Surface Models" by Fuad Yassin et al.

Anonymous Referee #2

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The paper "Representation of Water Management in Hydrological and Land Surface Models" presents a new scheme for representing reservoir operation in large-scale hydrological and land-surface models. The paper is relevant to HESS readership. It starts by providing a relatively good review of the reservoir operation algorithms both in operational and large-scale models, although several new contributions have missed (please see below just as a sample). The paper is well-written, particularly in the first two sections and the way different algorithms are classified is interesting because it provides a fresh perspective on taxonomy of existing reservoir operation models. The algorithm proposed is simple conceptually and therefore is suitable for the application suggested, although it may end up awfully over-parameterized, in the case of suggested configuration when storage/release thresholds are updated at each month.

This makes the algorithms very limited in scope because the data support for such parametrization is not available in many places of the globe, even in North America despite what mentioned in the paper. Overall, the paper makes a modest contribution to the discussion around representing reservoir operation in large-scale models by providing a new modeling hypothesis, however while the pros of the algorithm is well highlighted, the cons are not really discussed. In addition, I do not believe a new reservoir algorithm, which potentially requires a lot of parameters and cannot represent the dynamics of water withdrawals, can solve the diverse set of grand challenges embedded in "Representation of Water Management in Hydrological and Land Surface Models".

As a result, I do agree with the Anonymous Referee #1 that the contribution made is largely oversold. Finally, some of the details in the modeling and results should be better summarized and very important implications, particularly on the trade-off between representing reservoir storage and release, should be better discussed. I suggest the paper undergoes major revisions to address the specific issues raised below:

We would like to thank the reviewer for all the helpful comments and for the time spent to carefully review our manuscript. We present our response to the reviewer's comments below. The reviewer comments are listed below in regular, black text, and our response in regular blue text.

We appreciate the above important point raised by the reviewer. Since each of the reviewer's above points are separately expanded below, our response addresses the above point in the appropriate section of the numbered list below.

1) The title should be changed: A new reservoir algorithm cannot solve all problems in representing water management in large-scale models.

We agree with the reviewer that the original title was misleading, and as per the objective and contribution of our work, we are suggesting the following title for our revised manuscript: "Representation and Improved Parameterization of Reservoir Operation in Hydrological and Land Surface Models".

2) Although pre-2015 contributions are covered relatively well, new contributions are largely overlooked. Please update the literature review. The contributions named below are just a very limited sample of important new contributions missed in the paper and are given only to help authors to start refurbishing their introduction and framing their algorithm in a wider context:

Pokhrel, Y. N., Hanasaki, N., Wada, Y., & Kim, H. (2016). Recent progresses in incorporating human land–water management into global land surface models toward their integration into Earth system models. Wiley Interdisciplinary Reviews: Water, 3(4), 548-574.

Hanasaki, N., Yoshikawa, S., Pokhrel, Y., & Kanae, S. (2018). A global hydrological simulation to specify the sources of water used by humans. Hydrology and EarthSystem Sciences, 22(1), 789.

Ehsani, N., Vörösmarty, C. J., Fekete, B. M., & Stakhiv, E. Z. (2017). Reservoir operations under climate change: storage capacity options to mitigate risk. Journal of Hydrology, 555, 435-446.

Masaki, Y., Hanasaki, N., Biemans, H., Schmied, H. M., Tang, Q., Wada, Y., ... & Hijioka, Y. (2017). Intercomparison of global river discharge simulations focusing on dam operation at multiple models analysis in two case-study river basins, Missouri–Mississippi and Green–Colorado. Environmental Research Letters, 12(5), 055002.

Solander, Kurt C., John T. Reager, Brian F. Thomas, Cédric H. David, and James S. Famiglietti. "Simulating human water regulation: The development of an optimal complexity, climate-adaptive reservoir management model for an LSM." Journal of Hydrometeorology 17, no. 3 (2016): 725-744.

Coerver, H. M., Rutten, M. M., & van de Giesen, N. C. (2018). Deduction of reservoir operating rules for application in global hydrological models. Hydrology & Earth System Sciences, 22(1).

We thank the reviewer for the suggestions. Some of these papers were not included in the original manuscript, because their contribution about reservoir operation was minimal; however, we are currently examining the suggested references and some other more recent papers to be included in the revised manuscript.

3) Section 3.3: The authors suggest updating the storage/release parameters on the monthly scale to represent the seasonality: So should we end up with 72 parameters for a single reservoir?! Is this something really suitable for using in the context of large-scale models that have already a lot of parameters and face with scarce and low quality observations particularly in terms of human-water interactions? Because of being heavily over-parameterized, this scheme is only suitable where there are at least multiple years of continuous and high quality data available: Even in North America, such data availability is widely limited considering the discontinuity in in-situ measurements of storage and release across regional reservoir networks even in western Canada and US, where most of the case studies of this work are located. The fact that many large dams are privately owned and therefore the data are not publicly available is not mentioned anywhere in the paper: This is the particularly the case of large hydroelectric dams in US, Canada and Brazil that together account for large proportion of annual reservoir storage globally. Please discuss properly this important issue of the scheme along with other limitations of the proposed model at least with the same weight as its strengths. Highlighting the limitation of the proposed algorithm must be a key consideration during revisions.

We agree with the reviewer that the DZTR scheme become over parameterized. However, its parameters are external to those of land surface model and are determined a priori from storage and release data. The decision of the time scale to use for specifying the parameters is left to the modeller. Given that storage (or level) and outflow data are required to calculate the parameters, the modeller will have the ability to see the seasonal patterns of the data and decide whether a monthly or a coarser time scale (e.g. quarterly) would be sufficient. The scheme is flexible in that regard. On the data issue, the actual operation rules are not usually known for privately owned reservoirs and that is why we are inferring them from release and storage data. Releases can be estimated from the nearest downstream station if direct releases are not available. Water levels of reservoirs are widely available and can be converted to storage data using the level volume relationship if known or a generalized one if not known (Liebe et al., 2005). If the data to parameterize the scheme cannot be found or reasonably estimated, then a simpler scheme like Hanaski et al. (2006) could be used.

The other point to keep in mind is that a land surface hydrology model can have several reservoir operation methods in parallel and use a reservoir identifiers as to which method to use for each reservoir. In a large scale modelling context, one would only consider reservoirs that have a considerable impact on the flow regime and those will tend to be larger important ones that have reasonable flow and level records. As shown in Figure 4, we checked the reservoir locations in Canada and many of major ones have Water Survey Canada level records. Additionally, Alberta Environment and Parks make available such data for most reservoirs within Alberta (https://rivers.alberta.ca/). Similar high quality data is available for some basins in the US as well (Upper Colorado: https://www.usbr.gov/rsvrWater/HistoricalApp.html, Texas: https://www.waterdatafortexas.org/reservoirs/statewide). The manuscript is being revised to discuss those data issues and limitation to wider applicability of the DZTR scheme. Obtaining water level and flow data via satellites (Busker et al., 2019) may alleviate the issue in the future as discussed in the manuscript.

4) Section 4.1: What are the uncertainties in the generalized parameterizations? The percentiles corresponding to monthly target storage and release should be different for different reservoirs and I can imagine that it might be several combinations of percentiles that can provide similar modeling efficiency even in one single reservoir: Please discuss and provide some evidence on the uncertainty in these generalized parameterizations.

We agree with the reviewer that the uncertainty aspect has been overlooked in the manuscript. The following discussion points to the direction and scope we are following in the revised manuscript:

Reservoir operation on its own involves considerable uncertainties that is attributed to several factors. One major source of uncertainty in reservoir operation is future inflows (long-term and short-term inflow forecast). The forecast contains errors deep-rooted in the forecast method, the driving climate forecast, snowpack measurements, timing of snowmelt and the statistical (stationarity) assumptions to generate inflows based on historical inflows. The inflow forecast uncertainty is more significant during flood seasons because it involves subjective decisions of operators to averse the risk of dam overtopping and downstream flooding. Other sources of uncertainty in reservoir operation include changes in demand over time because of increases in demand for irrigation, power, water supply, etc. The purpose of the reservoir can also change from its initial intended purpose (e.g. adding a hydropower station to an irrigation dam). These changes are only implicitly captured by the DZTR scheme as implied in the storage and release time series used for parameterizing it for a specific reservoir.

Given the above uncertainties, even the actual reservoir operation may deviate from the designed reservoir operation rule curve. Some of the decisions of reservoir operators are spontaneous, ad-hoc, and depend on experiences that are not usually documented. Thus, there are difficulties to accurately represent the historical operation or to establish accurate relationships between reservoir storage, inflow, and release. These relationships typically contain considerable noise e.g., different release values at the same storage level during the same season. As a result, these uncertainties considerably influence the parameterization of the model derived to represent the reservoir operation based on historical observations of each reservoir. This is particularly true for the algorithm presented because of two main factors. Firstly, the presented reservoir algorithm assumes that the relationship between reservoir storage and releases follow piecewise linear functions. There is a chance that other functional forms represent such relationship better for some reservoirs. Secondly, in the case of the generalized parameterization, the piecewise bending points (zone classification points) are estimated based on fixed probabilities of exceedance extracted from historical data for all reservoirs. A different dataset (of reservoirs and/or time periods) could result in different quantiles. The assumption of having similar bending points of the piecewise linear functions for all reservoirs cannot provide optimal zones for each reservoir. However, this is true for any type of generalization of parameters and we showed that the generalized parameterization performs better compared to other widely used algorithms. One way to reduce such type of uncertainty is to optimize the parameters based on observed data if it is available. Using all the optimal solutions usually encompasses the observed behaviour within a narrow bandwidth as shown in the example plot below. This model with parameterized using all the data available for Trinity reservoir in the US (Figure 1).

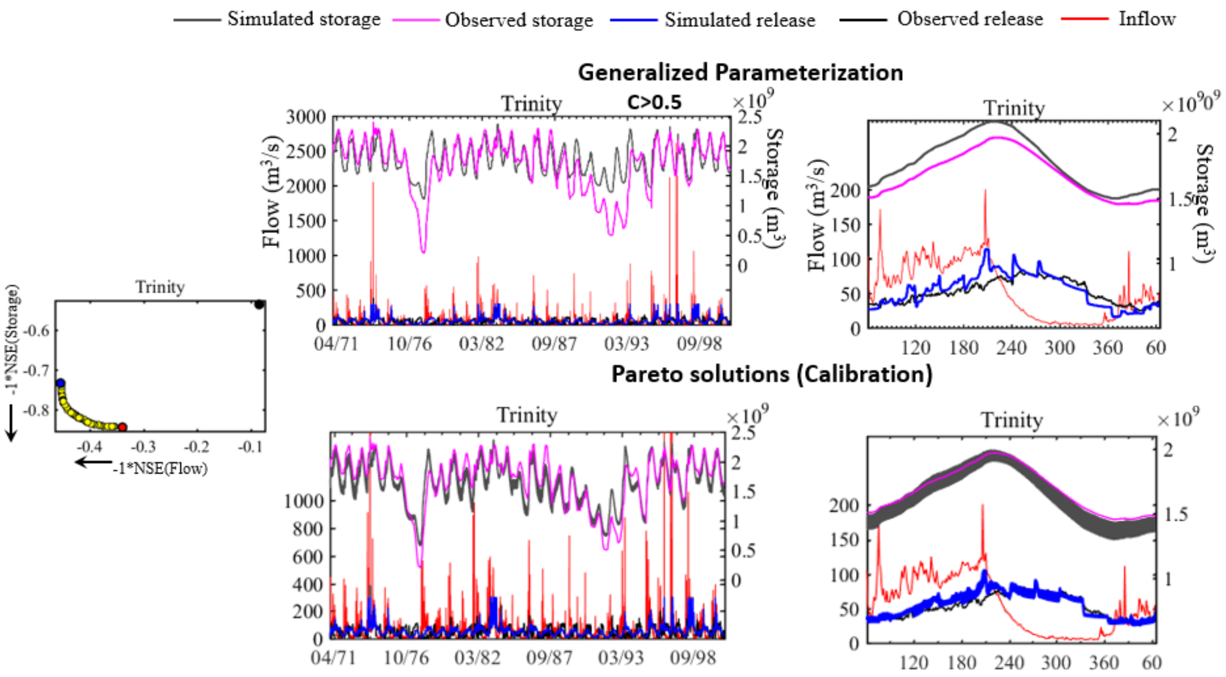

Figure 1: comparisons of Trinity dam simulation with generalized parametrization and multicriteria calibration

5) Figure 11 in the shows an explicit trade-off between reservoir release and reservoir storage during calibration: This means that it is impossible to reach the skill in representing each objective function without compromising on the other, implying that the algorithm is unable to track both

reservoir release and storage optimally at the same time: Isn't it a limitation in the model? How much this uncertainty contributes into uncertainty in identifying the role of reservoir in modifying the natural streamflow regime? This very important point seems to be wholly ignored at this stage and should be addressed in revisions.

Thanks for raising this point. This is being elaborated in the discussions in the revised manuscript as follows:

Only in the case of a perfect model and perfect data the trade-off between objectives converge to single point. The proposed model, like many other types of model is not an exception because of the uncertainties discussed in the previous point. Thus, the trade-off between storage and release objectives can be viewed as a measure of evaluate the limitation of the reservoir algorithm (piece-wise linear functions, fixed number of zones, etc.) and observation errors. To examine the level of uncertainty of the trade-off, it is important to look at the shape and range of the trade-off on each objective function axis.

As shown in Figure 11 in the manuscript, except for few reservoirs, the value range of Pareto solutions for each objective function is generally narrow (check the axes) with good NSE values. In such cases the associated uncertainties are minimal and the trade-off between improving simulated releases and improving simulated storage is minimal. The figure above is a good example of this case, it shows how the simulations of reservoir release and storage using the parameter sets of the Pareto solutions enveloped the majority of the storage and release observations within a narrow uncertainty band. Conversely, in some cases, the extended spread of the tread-off in one of the axes (objective function) are observed, indicating a higher uncertainty of the algorithm or parameter sensitivity for the process the axis represent i.e. reservoir storage or release. This indicates further investigations of the datasets and parameterization for those reservoirs and their history of operations. Shifts in operational management of reservoirs do occur and these may obscure the parameterization. These may be detected by careful examination of the available records as well as metadata records of the reservoir history if accessible. The level of noise when determining the parameters could be an indicator of changes in operation.

Overall, given the good performance of the algorithm for almost all reservoirs using both the generalized and calibrated parameterization, it is suitable to simulate the effect of reservoir in modifying the natural flow regime with less uncertainty compared to other methods.

6) Figure 11 again: It is surprising that the results during validation do not show the trade-off observed during calibration in several reservoirs: Doesn't this show that the parametrization is very sensitive to the period used for parameter identification? Also, the results during calibration are non-dominated by definition; however, do the results during validation also remain non-

dominated when compared with other possible parametrizations that have been dominated during the calibration? The sensitivity of model parameters to training data and the robustness of results during validation should be well discussed during the revision and supported by experimental results.

Thanks for pointing this point out. We are incorporating this issue in the revised manuscript as:

Indeed, the calibration period used to identify the parameters influences the performance and shape of the Pareto front during validation period. One of the reasons the calibrated Pareto solution does not show the same trade-off during validation is when there is considerable change of inflow as a result of consecutive wet or dry years. As shown below (Figure 2) as an example for Glen Canyon (similarly Bhumibol, Fort Randall, Fort Peck), the calibration period has more wet and high inflow years than the validation period. Such considerable change of inflow, storage, and release results in performance failure during validation period.

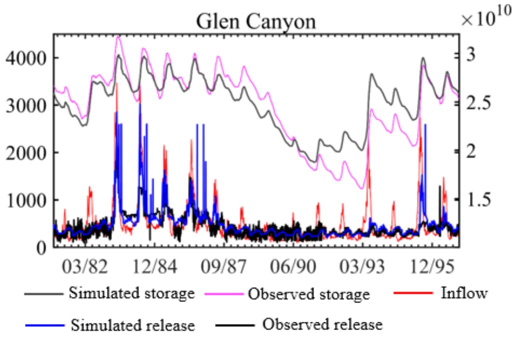

Figure 2: Simulation of Glen Canyon dam with generalized parametrization

A small change of inflow, storage, or release in the validation period can change the shape of the trade-off, however, the calibrated parameters was still capable of reproducing good performance during validation close to or better than the generalized parameterization performance.

For the sake of demonstration, we calibrated the mentioned reservoirs using the whole observational record and all of them show the trade-off between storage and release fitting (please see the Figure 3 on the last page). Thus, we recommend using as much data as available to parameterize the model for a specific reservoir.

7) Incorporation of the algorithms in the considered large-scale model seems to be limited to one reservoir at the time. Whereas in real cases, multiple reservoirs are built over one river and therefore the cal/val procedure and the skill of the reservoir algorithm should be tested when the outflow from one reservoir is the inflow to the next reservoir. The paper ignores this as many other similar contributions do. But I believe this is worth at least proper discussion because the challenge

is out there and has remained, indeed, unsolved. Up to the time that the problem of considering multiple reservoirs in one basin is not properly solved, the results of large-scale models remain only as naive simulations of a virtual hydrologic reality at the basin-scale, which contributes to a huge uncertainty at regional, continental and global scales.

Thanks for pointing out this issue. It is indeed a major challenge to accurately represent reservoir operation for a cascade of reservoirs. The parametrization and formulation of the algorithm implicitly accounts, to some extent, for the upstream regulation effects from the upstream cascade reservoirs. This is because the regulated inflow is used for parametrizing downstream reservoirs. The regulated inflow is assumed to reflect the regulation of upstream reservoirs in the cascade. In reality, the operations of some cascade reservoirs are highly interlinked, particularly during the flood season. The decision regarding the release from one reservoir accounts for the (forecasted) state of other reservoirs. Such dual- or multi-linked operation is however not accurately accounted in the presented algorithm because it assumes that each reservoir operates using its own storage state, inflow and target storage and releases. Such systems require detailed modelling of operations that is not usually attainable in large scale hydrological models. Depending on the purpose of the model, the modeller may decide to lump those reservoirs together to improve simulations downstream. The issue raised is a general issue with the state of the art, and we agree that, as a community, we should look for innovative ways to handle the issue. In the revision, these discussion and clarification are being expounded.

References:

Busker, T., de Roo, A., Gelati, E., Schwatke, C., Adamovic, M., Bisselink, B., Pekel, J.-F. and Cottam, A.: A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry, Hydrol. Earth Syst. Sci., 23(2), 669–690, doi:10.5194/hess-23-669-2019, 2019.

Liebe, J., van de Giesen, N. and Andreini, M.: Estimation of small reservoir storage capacities in a semi-arid environment: A case study in the Upper East Region of Ghana, Phys. Chem. Earth, Parts A/B/C, 30(6–7), 448–454, doi:10.1016/J.PCE.2005.06.011, 2005.

Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, Döll P, Endejan M, Frenken K, Magome J, et al. 2011. High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment* **9** (9): 494–502 DOI: 10.1890/100125

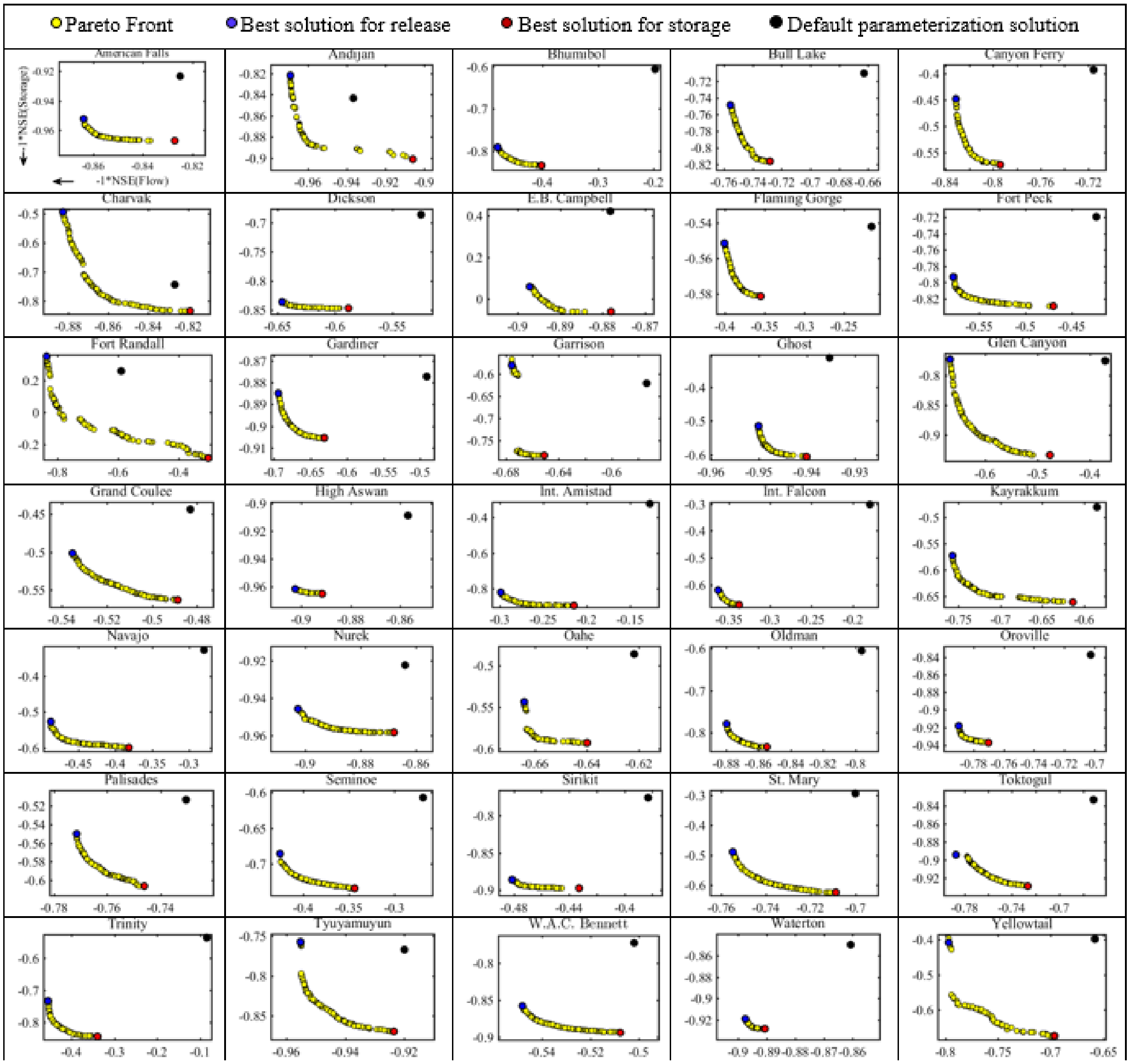

Figure 3: Calibration using the whole observational record

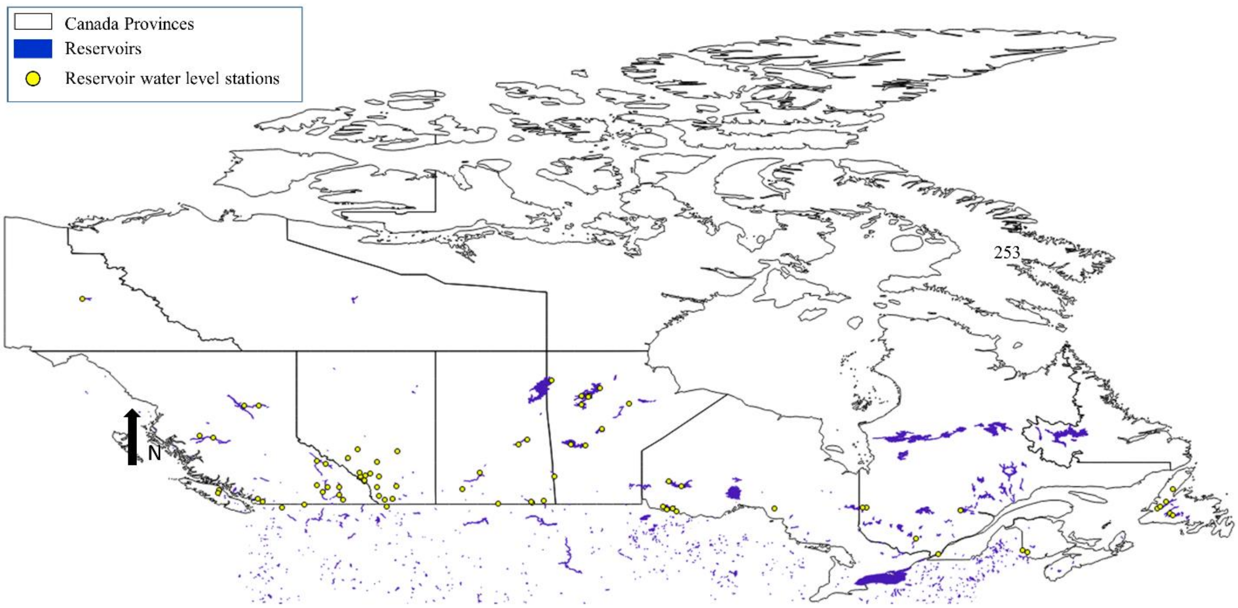

Figure 4: Reservoir water level stations of Water Survey Canada