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Automatic calibration of river reach 2D simulations based on SRH-2D

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ABSTRACT

River model calibration is essential for reliable model prediction. The manual calibration method is laborious and time consuming and requires expert knowledge. River engineering software is now equipped with more complex tools that require a high number of parameters as input, rendering the task of model calibration even more difficult. This paper presents the calibration tool O.P.P.S. (Optimisation Program for PEST and SRH-2D), then uses it in multiple calibration scenarios. O.P.P.S. combines PEST, a calibration software, and SRH-2D, a bi-dimensional hydraulic and sediment model for river systems, into an easy-to-use set of forms. O.P.P.S is designed to minimize the user's interaction with the involved program to carry out rapid and functional calibration processes. PEST uses the Gauss-Marquardt-Lavenberg algorithm to adjust the model's parameters by minimizing an objective function containing the differences between field observation and model-generated values. The tool is used to conduct multiple calibration series of the modelled Ha! Ha! river in Québec, with varying information content in the observation fields. A sensitivity study is also conducted to assess the behaviour of the calibration process in the presence of erroneous or imprecise measurements.

Keywords: river modelling; automatic calibration; parameter estimation; SRH-2D; PEST

1 Introduction

River models are used in various ways by engineers in many fields. These models are relied upon to assess problems that cannot be studied directly or that are too complex to be addressed via simplified approaches. River models are generally oriented towards predictions in many environmentally oriented fields of study, such as water quality, flood prediction and sediment transport.

In most study cases, the process of building a functional model comprises four main steps (Vidal et al., 2007): model set-up, model calibration, model validation and exploitation. Model calibration, being an essential and crucial step, consists of the adjustment of the model's parameters until a satisfactory agreement between simulated values and measured values is obtained. Hydraulic models include a certain variety of parameters that cannot be measured or assessed via field measurements or observations. Reliable model predictions will therefore be obtained through a thorough calibration process (Bahremand & De Smedt, 2010).

The manual calibration task is commonly performed in a trial and error process where the user progressively adjusts the parameters until a satisfactory result is obtained. This method is limited since the task is time consuming and the subjectivity of the quality of the adjustment highly depends on the user's experience (Boyle et al., 2000). Moreover, the number of variable parameters is often reduced as much as possible by the users to reduce the model's complexity. With the ever-growing computational capabilities of the models and the increasing demand for model precision, the manual calibration method sometimes becomes inappropriate.

Dedicated studies have aimed to develop efficient and automatic calibration methods where the parameters are adjusted until an objective function is brought to a minimum. Calibration methods come in two forms: the global methods based on an evolution algorithm, such as the Shuffled-Complex Evolution method (Duan et al., 1992), and the gradient-based methods, such as the Gauss-Marquardt-Levenberg algorithm. Global methods are robust in finding the minimum of the objective function in the entire parameter space but require a great amount of model runs to achieve this result. Gradient-based methods on the other hand are computationally efficient, but the result can sometimes be dependent on the initial parameters as the calibration progresses from an initial set of parameters towards the steepest descent of the objective function.

Model calibration, regardless of the chosen method , should be done with caution as multiple parameter sets of model structure could exist and yield equally acceptable results (Beven & Freer, 2001). The existence of these different possibilities is known as “equifinality” and has been well documented before (Pathak et al., 2015). The issue of equifinality is not the main focus of the authors in this study but rather the application of a “work-around” technique to avoid it.

Though the hydraulics models have evolved into complex tools with diverse functionalities to visualise and present results, calibration-oriented tools have not progressed in the same manner. Additional features have been implemented in the models to yield more capabilities in data presentation, but little has been done regarding the improvement of the calibration tools: “evolution of calibration support mechanisms has yet to undergo the same level of development as the models themselves” (McKibbon & Mahdi, 2010). Vidal et al. (2007) depicted the same problem: “even modelling packages promoting good modelling practices do not provide significant features to assist users during manual calibration”.

For the same solver, or software, even if PEST (Parameter ESTimation) can be used to calibrate a particular river model (Lavoie and Mahdi, 2016), the tedious calibration process has to be repeated again for a new river model even if using the same solver. To facilitate the calibration process, an automatic calibration tool is created that combines PEST and SRH-2D (Sedimentation and River Hydraulics). To the knowledge of the authors this is the first time that a tool based on PEST is developed to calibrate any river model based on the SRH2-D, a 2D free hydrodynamics software developed by the USBR (U.S. Bureau of Reclamation). The user simply specifies the parameters he wishes to submit to the calibration process and the observation values to be compared with the simulated results. The developed tool then assures the entire configuration and execution of the calibration process.

The tool created is then used to explore different calibration scenarios where the effect of progressively increasing the available information used by the calibration process is considered. Another set of calibrations is undertaken with the introduction of an error in the measurement values to explore the effect of erroneous data. This paper deals only with the calibration of the Manning's roughness coefficient.

2 Methods

This section introduces the hydrodynamic model used for the river reach flow simulation, SRH-2D, and the optimisation program PEST. The tool developed is also presented, along with the description of the conducted calibration series on the model.

2.1 SRH-2D

SRH-2D (Lai, 2008) is a depth-averaged flow and sediment transport model for river systems that was developed at the U.S. Bureau of Reclamation. The software is capable of simulating flow through multiple reaches, floodplains, vegetation lands and hydraulics structures. SRH-2D is well suited for rivers that require a better representation of 2D effects, such as multiple flow paths or in-stream structures. It computes the local water elevation, local flow velocity, eddy pattern and shear stress on riverbeds and banks. The software is built to easily divide rivers into different reaches depending on vegetation, topography or morphology. The hybrid meshing strategy is well suited to zonal modelling as it allows for both a quadrilateral and triangular shape with the desired density.

An implicit scheme is used to solve the finite-volume numerical method based on the 2D depth average dynamic wave equation of St. Venant. Steady and unsteady state can both be simulated by the software, and all flow regimes may be simulated. For a better understanding of the model, additional details can be found in Lai (2009), where a complete description of the governing equation and discretisation methods is displayed. Although SRH-2D is capable of computing sediment transport, this model is considered static and therefore does not include aggradations or degradation of the riverbed.

Pre-processing and post-processing of the model is executed in SMS (Aquaveo, 2013), a modelling software presented as a graphical user interface and analysis tool that holds all of the SRH-2D functionalities.

2.2 PEST

To verify the reproduction of the physical phenomena by the model, the data calculated by the model needs to be compared with measured values to determine the model's performance regarding the reproduction of the said phenomena. Based upon the assumption that the model responds to an excitation or an impulsion, it is possible to imagine that there is at least a combination of parameters that can make the model reproduce the same reactions that occur in the modelled environment (Doherty, 2010).

PEST is a model-independent software designed to assume the task of calibration in a completely automatic manner by applying the Gauss-Marquart-Levenberg algorithm (Doherty, 2010). The calibration is undertaken by reducing to a minimum the objective function, which holds the discrepancies between the measured values and the results given by the model. PEST will gradually adjust the model parameters following the steepest descent towards the minimum of the objective function until it reaches the user-supplied termination criteria. The parameters obtained would hence give the best match between the supplied measured values and the simulated values.

The parameter estimation is based on a linearization of the relationship between the model parameters and the calculated output values. At every iteration, PEST executes as many model runs as there are calibration parameters to generate their partial derivatives using a user-guided finite difference. Following every model run, PEST examines the output information and, based on the instruction supplied in the control files, will refine the input parameters of the model towards the predicted steepest descent of the objective function based on the calculation of the Jacobian matrix of the model parameters. PEST will stop this process once the objective function is reduced to a minimum.

To conduct this task, PEST takes control of the model by executing it as many times as needed while modifying the parameters until the objective function is lowered to a user-supplied satisfactory level. PEST requires a specific set of instructions in the form of three files. The first file indicates the way in which the output information generated by the model should be interrogated. The second is a mirror image of the input file, which is used to locate the calibration parameters. The third file is the centre of command of the whole operation and contains all the instructions regarding the calibration process (Doherty, 2010). The content of these files will vary from one model to another.

In this unique approach, PEST is linkable to almost any type of model as long as the input and output information can be accessed in any way. The sequential execution of the model by PEST is accomplished via a batch file, which can be a succession of multiple operations such as the translation of the output file to a readable format or the combination of multiple information coming from the model resolution. PEST has already been proven to be an effective calibration procedure for hydrological models and quasi-2d hydrodynamic models (Diaz-Ramirez et al., 2012; Ellis et al., 2009; Fabio et al., 2010; Kim et al., 2007; McCloskey at al., 2011; McKibbon & Mahdi, 2010; Rodeetal., 2007)

2.3 O.P.P.S.

The Optimisation Program by PEST for SRH-2D (O.P.P.S.) is the resulting tool for the automatic calibration of SRH-2D by PEST. O.P.P.S. eases the task of preparing the calibration process by correctly building the required files with the user's desired PEST regularisation parameters. O.P.P.S. comes in the form of an easy-to-use graphical interface based on Excel® Visual Basic, where the user can quickly specify the current project's parameters to be calibrated and the measured values that are to be matched in the model.

O.P.P.S can easily prepare and execute an operational PEST calibration process with minimum user interaction. The model is sequentially launched by a command line in the form of an AutoHotKey® file capable of conducting single model runs without any user intervention. Indeed, the execution of the command lines supplied with O.P.P.S. allow for carrying out the calibration process in the background without the user interventions normally required by SHR-2D. A single non-calibration run would normally require multiple human-directed operations that would interfere with the automatic aspect of the calibration process. Therefore, the automatic execution of SRH-2D is made completely free of user interventions.

When O.P.P.S. is launched, the interaction with the user is made through a series of forms in which the information regarding the calibration process can be entered. A summary of the procedures followed during the preparation and execution of the calibration process is presented in figure 1. Any combination of measured depth, water velocity along the X- and Y-axis, and the velocity magnitude at any point in the model can be supplied as observation values to be compared to the simulated results for each observation point. The measured values supplied are individually used in the calibration process: there will be as many single observation points as there are measured values in the calibration process.

The subsequent preparation steps are carried out by O.P.P.S. and the calibration process is guided by PEST. Once the parameters and the observation points have been identified, O.P.P.S can create the required files for PEST's execution. A series of verifications are performed to avoid errors or performance issues that can arise when PEST is not efficiently programmed. If it does not exist already, O.P.P.S. will automatically create a backup file of the project. When PEST is executed, permanent changes will be applied to the selected parameters. Additional options for the fine tuning of the calibration process are also available.

Additional parameters can be adjusted for the fine tuning of the calibration process by managing the evolution of the calibration process.. The user can adjust the Marquardt-Lambda parameter, which guides the progression vector towards the optimal reduction of the objective function. The progression vector is gradually reduced as PEST progresses closer to the minimum of the objective function. PEST is presented with multiple decision criteria that can be adjusted by the user, depending on the project at hand. These criteria handle the conditions required to progress towards a new iteration or to terminate the calibration process at the most appropriate moment. In both cases, these regularisation parameters can be based on the evolution of the calibration parameters or on the progression of the objective function. . These parameters should be adjusted according to each project, as one configuration might not satisfy every calibration operation.

2.4 Study case

O.P.P.S. can quickly and efficiently assemble the required information to perform an operational automatic calibration process. This tool is used to perform a series of calibrations of the river model.In this study, the Ha!-Ha! River is partially modelled using the topographical data collected after the 1996 failure of a dam of the Ha! Ha! Lake. The dam failed as water rose rapidly during the high-yield rains that lasted for three days in the Saguenay region in Québec, Canada. The sudden flush caused an excessive increase in the river flow (more than 1000 m^3/s), drastically changing the river morphology by eroding the sediment deposit around the rocky bases of the riverbed. Capart *et al.* (2007) give the cross-sections data for every 100 m of the river.

The Ha! Ha! River basin covers a total of 572 km^2 in the Saguenay-Lac-St-Jean region, and its river stretches forth a total of 35 km from the Ha!-Ha! dyke to the river mouth, where it flows into the Saguenay river. The model comprises five different reaches of approximately 3 km each represented by different roughness coefficients. A map of the modelled reaches is presented in figure 2. The Manning roughness coefficient is the only adjustable parameter in the study case as PEST only allows for the calibration of continuous parameters. Although the calibration is limited to only one parameter, the roughness coefficient has been identified as the most influential source of uncertainty in river models (Hall et al., 2005; Warmick et al., 2010).

2.5 Calibration scenarios

The original set of parameters was established by the authors and were not measurements or calculated values. The hydrodynamic results generated by running the model with the original set of parameters were then used in the calibration process. Using the data recorded during the initial run with the original parameters as the observation values, PEST is expected to progress towards the initial set of parameters. Fictional parameter values were used by the authors because not enough data for this study case is available to proceed to a real calibration case. For each calibration scenarios, the maximum number of iterations allowed is 30 and the parameters can range from 0.01 to 0.1.The original values of Manning coefficients, along with the observation values used in the series of calibrations, are presented in table 1. The series of calibrations is carried out using different settings, with the number of observation points, their positions and their content varying in each series.

The calibration was performed on a IntelCore i5 2,27 GhZ laptop and required on average7 iterations and 60 model runs for the simpler cases and 10 iterations and 100 models runs for the more complex cases. Each model run take approximately 1 hour to complete.

2.5.1 Water depths

The first series of calibrations used an increasing number of observation points, only one per reach, containing only the observed water depths. In the first case, the calibration points were located close to the middle of the reach; in the second case, the points were located near the junctions of reaches or close to the boundary conditions. The first calibration used two observation points, while the subsequent calibration used one additional point, with a maximum of five (one per reach) in the first scenario and six in the second scenario.

2.5.2 Water depths and velocities

The next series of calibrations also used an increasing amount of observation points between each trial. In addition to water depths, observation points contained water velocity measurements: water velocity in the X- and Y- directions and the magnitude of this velocity. PEST now has access to an increased quantity of information to proceed with the calibration to explore the extent of adding information to the observation points. In all cases, the observation points are located near the centre of each reach. Each calibration process is carried out with identical instructions sets and regulation parameters and has the same starting values for the initial model run.

2.5.3 Sensitivity analysis

The next parts of the calibration series were used for a sensitivity study to observe the effects of introducing an error in the measured data used in the calibration procedure. Different scenarios were carried out using two different sets of observation data to aid in the calibration process, with a variable magnitude of the introduced error.

In the first case, the error was applied to the measured depth in a scenario where only the measured depth was available for the calibration procedure. In the second case, the same scenario as in the previous case was carried out by adding measured velocity data to the observation points to verify the advantages of additional information in the advent of an error in the data. Only the measured depth was subjected to the introduced error. The third case introduced an error in the model's input flow using all the available measured data of the observation points (measured depths and velocities). This scenario reveals the effect of flow overestimation and underestimation on the calibration. The first series of this case only included the measured depths at the observation points; the second scenario included all the measured data, i.e., measured depth and velocities. Again, partial use of the data in the first case was done to evaluate the benefits of adding additional data to the calibration process to better handle the possible introduction of error in the data.

3 Results and discussion

The results obtained in the different calibration scenarios are presented in this section, and the difference between the observed and simulated water depths of the entire model for the final calibration scenarios is shown. The results obtained from the calibration series and sensitivity calibration series are also discussed.

3.1 Water depths

The first series of calibrations only used a growing number of observation points containing the water depth as a means of correspondence between the model output values and the measured values. At first, only two observation points were supplied; for each subsequent calibration run, an observation point was added until each reach was supplied with a measured water depth. Figures 3 to 6 present the calibration results from the first series of calibrations.

Results show that PEST cannot correctly calibrate reaches without having at least one observation value in the reach, which in this case is the measured water depth. In each calibration process, the Manning coefficients in the reaches that are not supplied with an observation point have little or no variation compared to their starting values. From the observations made in the results, PEST needs to be supplied with at least one measured depth in a reach to correctly estimate the parameter value. However, PEST has no difficulty matching measured water depths, when supplied, in only a few model runs.

If, during the calibration process, PEST cannot find a correlation between the variation of a parameter and the reduction of the objective function, it will abandon further modification of the said parameter during the present iteration. This results in parameters that are left at their original values during the calibration process. Reaches that are left with an unvaried Manning coefficient have an influence on the upstream portion; thus, PEST, in its quest to match the featured values, must compensate for the unvaried coefficients with an overestimation of the Manning coefficient to reach the supplied measured value upstream. This is shown in the calibration results, where PEST could not correctly calibrate the reach 4 parameter when no information was supplied downstream in reach 3. When an observation point is added to reach 3, PEST can correctly adjust the Manning coefficients of both this reach and of reach 4.

Figure 7 shows the differences between the water depths recorded at the end of the calibration process using all the observation points and the water depths recorded with the original parameter values. The differences between the simulated values are very low considering that almost all the model's water depths are reproduced within a 0.005 m precision. The majority of the higher differences are located in reach 2, which is an area characterised by small instabilities in the results.

Since the low starting values of the Manning coefficient had a negative influence on the calibration results, the entire calibration series is reinvestigated by reinitialising the starting values in a range that would be much closer to a suitable estimation done by any user. This way, the calibration process could begin with starting values that could resemble a user's estimation.

The results obtained show the same result pattern with a much better performance in the calibration result since the starting values are closer to the original values. Like in the previous series, the reaches that are not provided with calibration points remain closer to their original values, but results show a positive movement towards the desired values as more points are added. In reach 3, the relative difference between the desired value and the calibration value is gradually diminished as additional points are added to the surrounding reaches. The same improvement is observed at reach 4, where overestimation caused by reach 3 is gradually reduced and much less exaggerated, similar to the previous calibration series.

Another calibration series was processed by using observation points located on the frontier of two reaches in the model to explore the “calibration value” of a different positioning of the observation points. The results showed that points placed on the frontier of two reaches facilitate only the calibration of the downstream reach; thus, one point per frontier is needed to obtain a proper calibration of the model. However, the uncalibrated reaches in this series did not have the overestimation effect upstream observed in the previous series.

3.2 Water depths and velocities

This series of calibrations also used an increasing number of calibration points, centred in their respective reaches, with additional measurements: each observation point featured the measured depths, the velocity along the X- and Y-axis, and the velocity magnitude. Figures 8 to 11 present the calibration results from the series of calibrations using water depths and water velocities of the observation points. With only two observation points (figure 8), PEST can find the desired values of 4 out of 5 reaches. The calibration parameter of reach 5 remained at the starting value, meaning that PEST could not establish a relation between the parameter variation and the reduction of the objective function.

As additional points are included in the calibration, the relative difference between PEST's suggested values and the desired values is gradually reduced. In fact, the quality of the adjustment increases faster with the addition of observation points and the model is calibrated to a satisfying status with less observation points. Additionally, reaches that do not have measured values to facilitate their parameter calibration can be estimated to a good level when upstream and downstream reaches contain calibration information. This is shown in the third calibration (figure 11), where the middle reach is correctly calibrated even without having any observation values attached to it. This series shows that less observation points are required to obtain satisfactory calibration results when the featured points contain more information.

Figure 12 shows the differences between the water depths resulting from the calibration process using all the observation points (water depths and water velocities) and the water depths recorded with the original parameter values. The differences are very similar to those of the calibration using only the water depths, with the exception of reach 2, which contains the majority of the higher differences from the original values. Compared to the calibrated Manning coefficient obtained in the other reaches, the value from reach 2 is overestimated, thus resulting in higher but still acceptable differences between the observed and simulated water depths. In the other reaches, the differences from the simulated water depth values are still within a 0.005 m precision.

The analysis of the results given by the hydrodynamic model shows that multiple points in the reach 2 area have oscillating results over time, meaning that the final solution might slightly differ from one simulation to another. The observation point used in this reach was carefully selected, ensuring that the instabilities in the point's solution were limited to minor variations. It is suggested that the additional observation values supplied in reach 2 were still affected by the instabilities met in the area, causing the parameter overestimation. Gonzalez (2016) also denoted some numerical instabilities in the modelled results.

Next, a sensitivity study is conducted by introducing an error in the measured values to explore the effects of using erroneous measurements during the calibration process. In the first calibration series, the error is embedded in the measured water depth of each observation point, and the calibration process is solely based on these values to approximate the parameter values. In the second calibration series, the measured water velocities are added to the observation points, without any errors. In the third series, the input model flow is varied and no error is introduced in the measured water depths or velocities.

3.3 Sensitivity analysis: water depth only

In the case where the error is introduced in the measured water depths and the calibration process relies on these values, the repercussions of the calibration error, presented in figure 13, are distributed in a linear fashion. From the previous calibration, we know that when five observation points containing measured water depths are supplied, the calibration results are almost perfect. The introduction of errors in the measured values raises the relative differences by a magnitude that depends on the surrounding topography of the reach. Portions of the river with floodplains or larger sections will suffer from more error, especially when the error overestimates the measured water depth, as it will require a higher friction coefficient to match the said value. Reach 1 and 2 suffer the most from the error introduction since they are the portions of the river with the steepest riverbed slopes and have more floodplains. Reach 3 is less affected since the channel is located in a much narrower area surrounded by steep hills.

3.4 Sensitivity analysis: water depth and speed

This calibration series is executed in the same manner as that of the previous one, with the additions of measured water velocities to the observation points. No error is introduced in these additional values. As figure 14 demonstrates, the relative differences of the calibrated values are lower than those obtained in the previous series. In this case, the maximum difference obtained is 20%, compared to 57% in the previous situation. The differences between each parameter in the individual runs of this series are less scattered, resulting in a flatter graphical display.

The most significant drop in relative difference between this series and the previous is recorded in reach 1, where the maximum recorded value drops down from a range of

15% to 47% to an average of 2%. The considerable reduction in relative error in this reach, which was previously highly sensitive to water depth variations, is the result of PEST adjusting the calibration parameter by prioritising the measured water velocities rather than the erroneous water depths. The results show that reaches that are more oriented toward fitting the measured water velocities rather than the water depths have the lowest relative error for the resulting calibrated parameter. This is shown in figure 15, where calibrated parameters with a better fit towards measured water depths (low relative difference between measured and calculated water depths) are more likely to be miscalibrated.

3.5 Sensitivity analysis: discharge

The next series of calibrations was carried out by introducing an error in the model's input flow. Both the measured water depths and velocities were used in the calibration process. Figure 16 shows the results of this series. The left side of the graph shows a linear relation between error induced in the model's input flow and error in the calibration parameter. The right portion of the graph presents a much more erratic relation with the flow augmentation.

Again, individual calibration runs that resulted in an accurate match between measured and calculated water velocities at the expense of matching the measured water depths are more likely to have more accurate results with the calibration of the Manning coefficient. Figure 17 shows the distribution of the relative error between the calibration parameters and the relative error between the observed and simulated water depth values and water velocity values – the relative errors of water velocities are summed. The Manning-water depth relation is much more concentrated on the left side of the graph, with a large variation in the relative errors of the Manning coefficient. This shows that when the calibration process adjusts the Manning coefficients, with a tendency to match the measured water depth rather than the water velocities, the calibration results are somehow more unpredictable.

4 Conclusion

This study presents the development of a tool combining PEST, an automatic calibration program, with the hydraulic model SRH-2D. The tool serves as an easy-to-use set of forms that can provide a rapid and functional linkage of a model with the automatic calibration tool. The amount of information required by the user and the user's interaction with the tool are minimized to provide a rapid preparation of the calibration process for the project at hand.

The tool was applied to the Ha! Ha! river model based on the post-flooding event of 1996, which drastically changed its morphology. The model comprised five reaches, each represented by a Manning roughness coefficient. An original set of parameters was used to generate observation values that were then used for multiple calibration series conducted to assess the effect of different scenarios on the calibration results. The positions, number and content of the observation points varied in the scenarios to establish the minimal calibration conditions and common guidelines for the usage of the tool.

The first series of calibrations used a growing number of observation points containing the measured water depth until each section was supplied with one observation point. The calibration results were optimal when one observation point was present for every reach of the model. Reaches without observation points led to miscalibrated parameters that negatively influenced the calibration of the upstream parameter. This negative effect on the upstream reach could be corrected by using observation points that are as far away as possible from the miscalibrated reach.

The results from another calibration series, where the measured water velocities were added to the observation points, showed that fewer observation points are required to yield satisfactory calibration results. The use of water velocities in the calibration process, combined with the water depths, indeed proved to be much more effective when estimating parameter values. Moreover, the additional information significantly reduced the calibration error when slight errors were introduced in the measure water depths.

A sensitivity analysis also showed that parameters that were calibrated by providing a better fit between measured and modelled water velocities presented better results. Indeed, parameters accentuating the concordance of water depths displayed a wide range of errors compared to velocities based on parameters that had a more predictable outcome regarding the calibration error.

It is suggested that the automatic aspect of the tool should be used to address the question of uncertainty and equifinality associated with the parameter estimation obtained through the calibration process. Additional scenarios should be tested to explore the continuity of the model performance or the continuity of the parameter estimation when the following calibration conditions are changed: parameter starting values, parameter range, observation values disposition, etc. Additionally, the calibration process should be revisited using different performance criteria based on a global evaluation of the modelled results or a subdomain measurement of performance. Pappenbergeret al. (2007) showed that the way of evaluating the model performance in the calibration process (i.e., objective function) has an impact on the results at different scales (local or global). Precaution must also be taken when assessing the calibration process as equifinality can be encountered when multiple sets of parameters may satisfy the fitting of the observation data (Beven & Freer, 2001; Pappenberger et al., 2005).

Considering the positive results obtained using the current build of O.P.P.S, further work should be done to include the sediment transport module of SRH-2D in the automatic calibration process. As of now, PEST does not include the calibration of discontinuous parameters, which could possibly cause problems considering that sediment transport parameters include integer-like input values. In this case, the calibration could be executed in two consecutive motions: the first would calibrate the continuous parameters; the second, using the calibration results of the continuous parameters, could iterate through a user-selected range of discontinuous parameters, selecting the set of parameters giving the best fit.

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Figures Captions

Fig O.P.P.S. flow chart

Fig 2 Ha!-Ha! river map and model overview

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Fig 4 Calibration results using water depths - 3 observation points

Fig 5 Calibration results using water depths - 4 observation points

Fig 6 Calibration results using water depths - 5 observation points

Fig 7 Overall water depths differences between original values and calibrated results using 5 observation points

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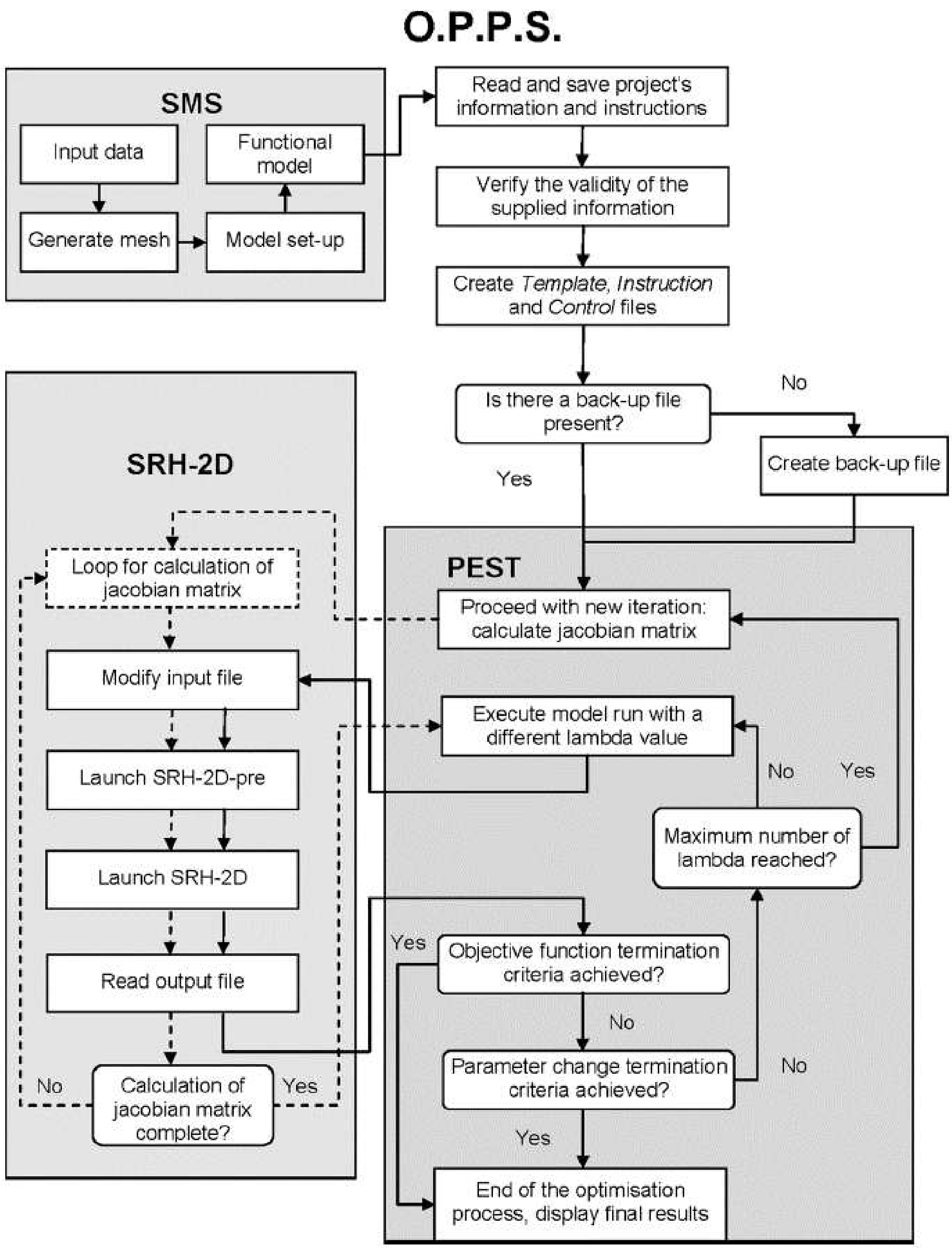
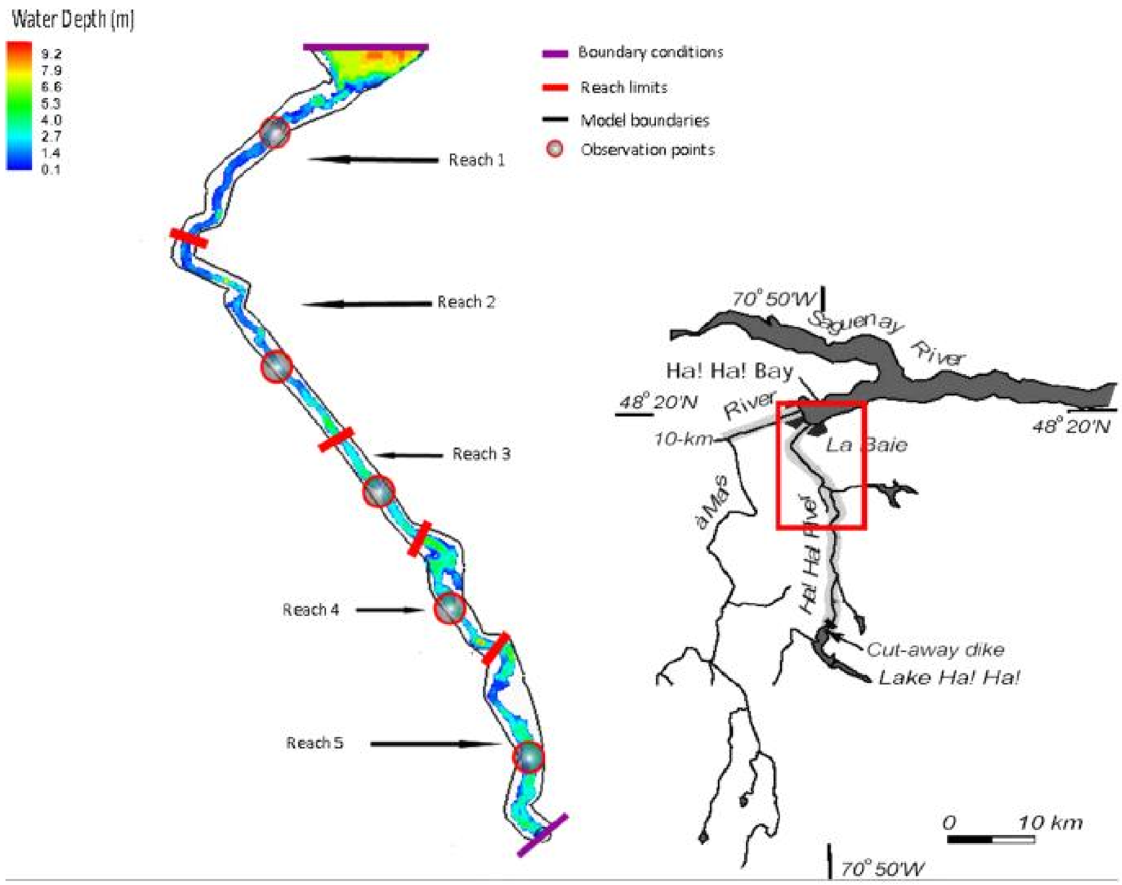
Tables

Table 1 Original values of the Manning coefficient and observation values

Reach number	Manning's coefficient original values	Observation point values			
		Water depth (m)	Velocity X (m/s)	Velocity Y (m/s)	Velocity magnitude (m/s)
Reach 1	0.02	1.416	1.146	0.941	1.481
Reach 2	0.028	2.786	-1.231	0.902	1.528
Reach 3	0.036	3.551	-0.559	0.526	0.769
Reach 4	0.026	3.463	-0.28	0.537	0.605
Reach 5	0.032	3.222	-0.215	0.367	0.425



595 **Fig. 1** O.P.P.S. flow chart



596 **Fig. 2** Ha!-Ha! river map and model overview

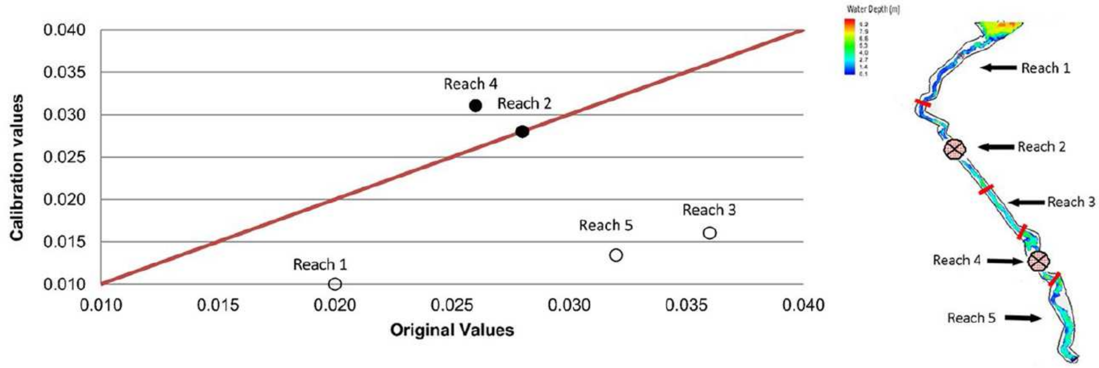


Fig. 3 Calibration results using water depths—2 observation points

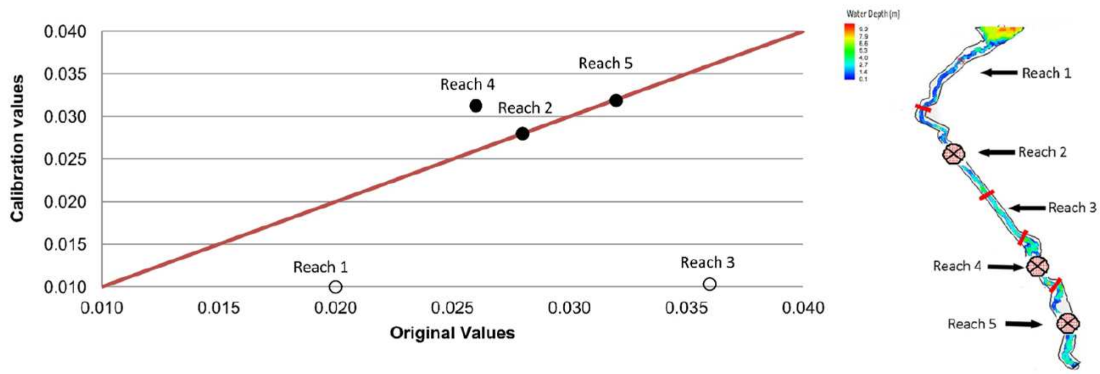


Fig. 4 Calibration results using water depths—3 observation points

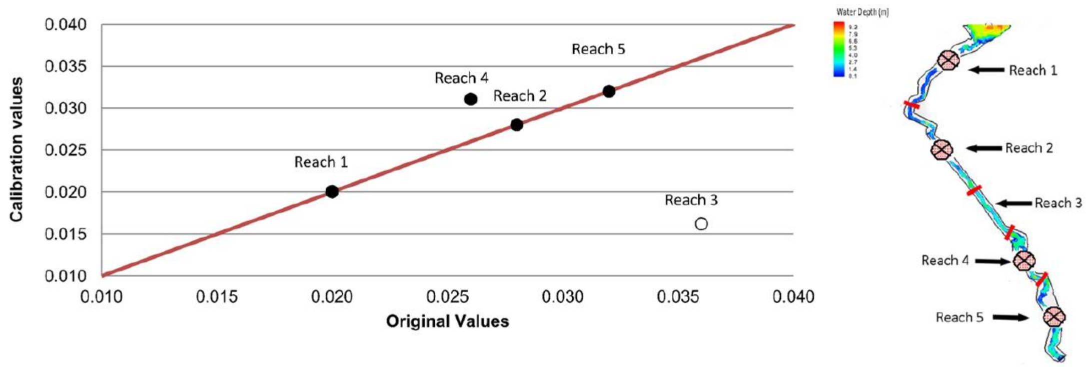


Fig. 5 Calibration results using water depths—4 observation points

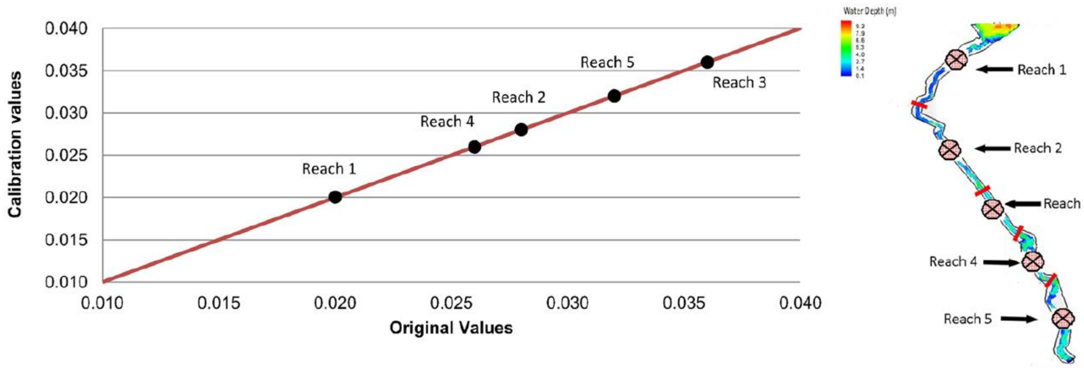


Fig. 6 Calibration results using water depths—5 observation points

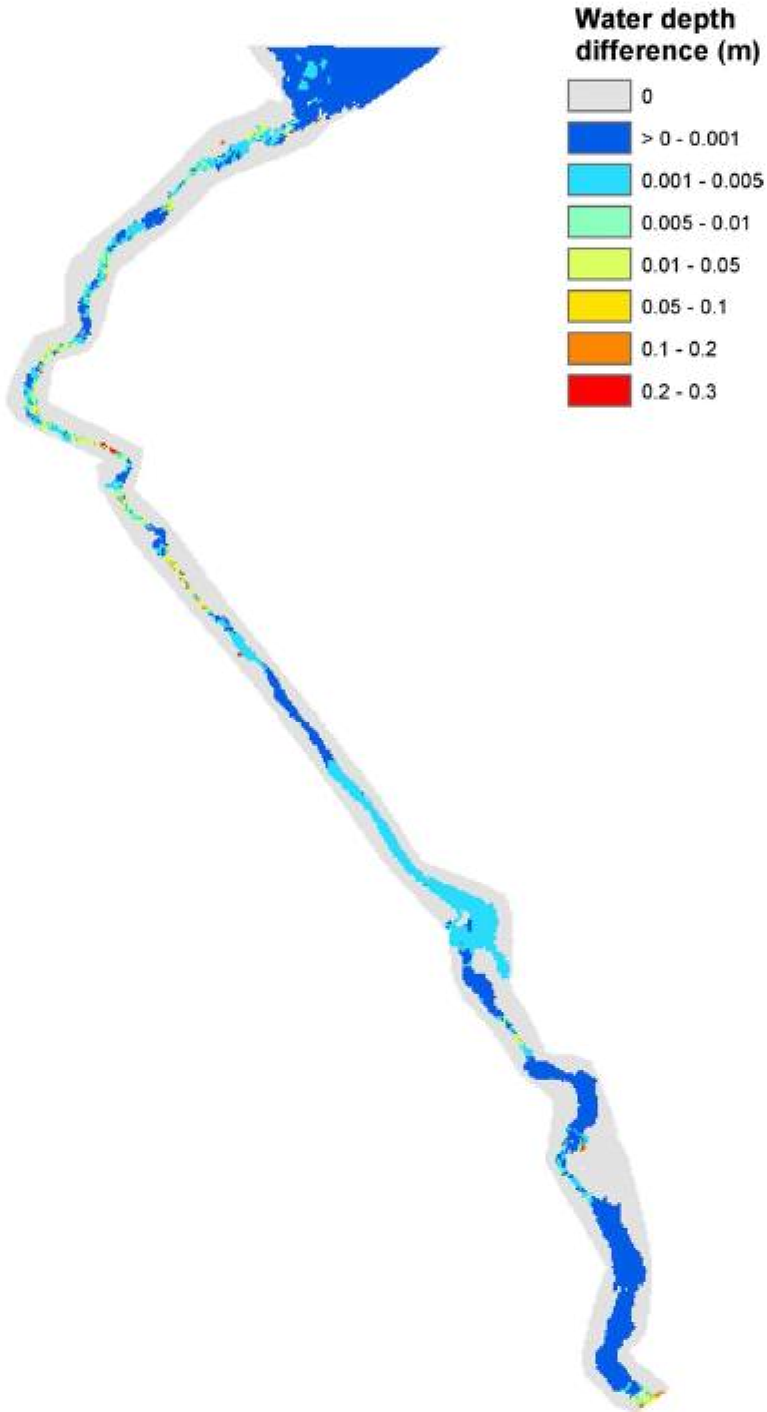


Fig 7 Overall water depths differences between original values and calibrated results using 5 observation points

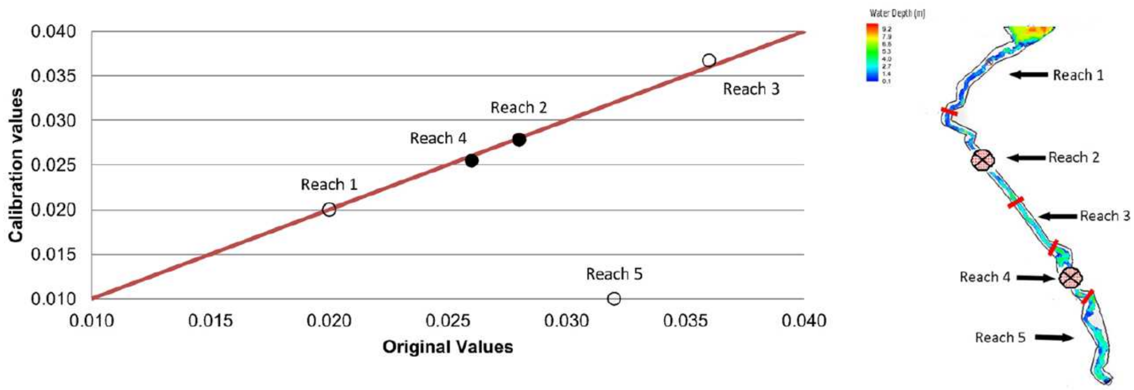


Fig. 8 Calibration results using water depths and water velocities—2 observation points

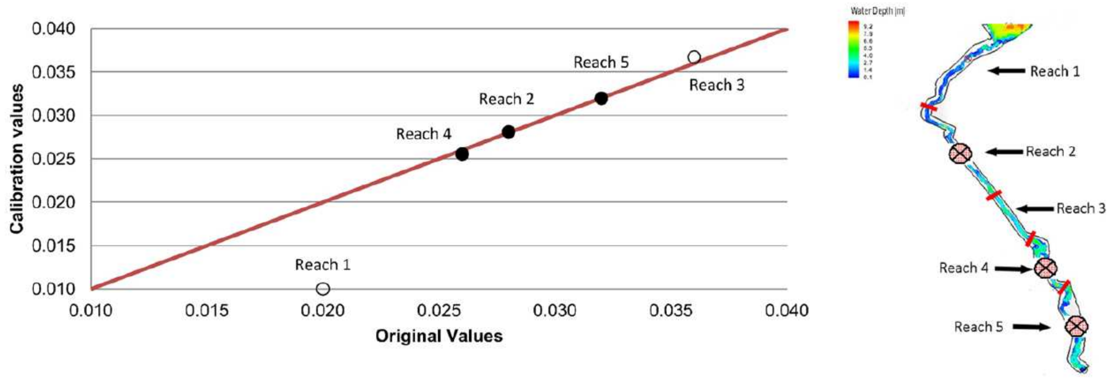


Fig. 9 Calibration results using water depths and water velocities—3 observation points

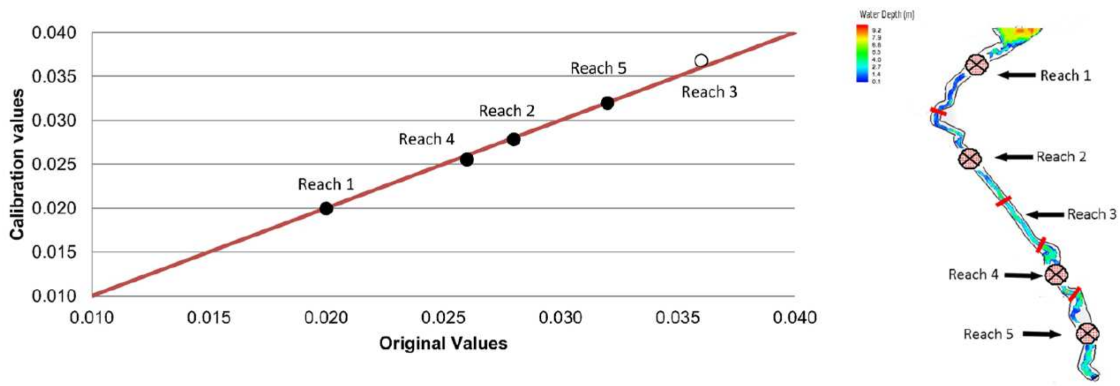


Fig. 10 Calibration results using water depths and water velocities—4 observation points

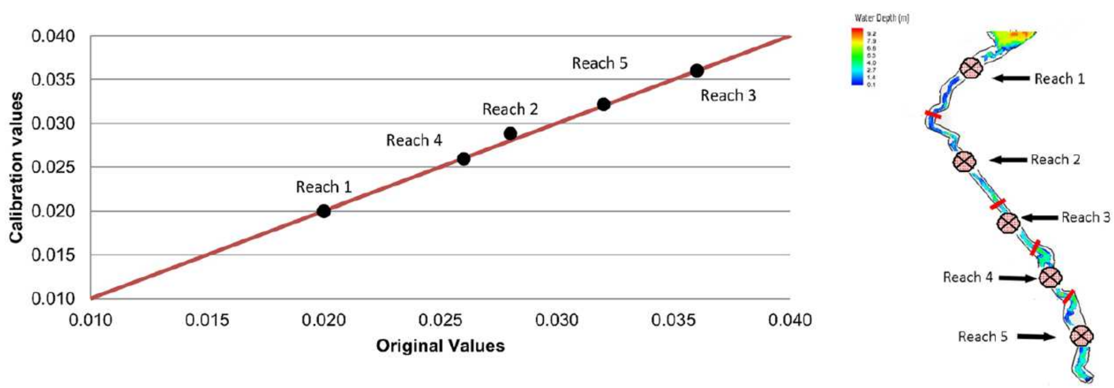


Fig. 11 Calibration results using water depths and water velocities—5 observation points

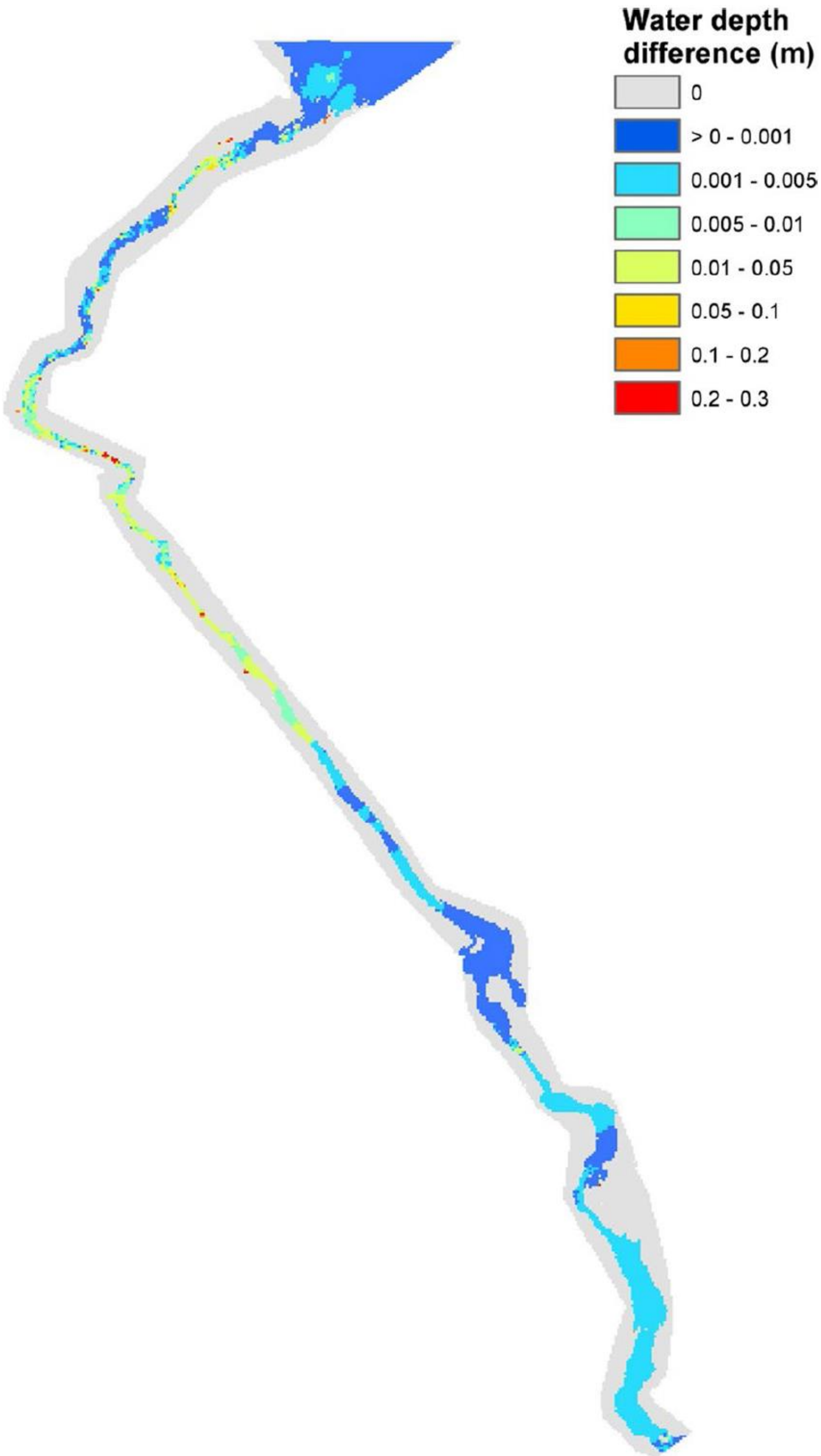


Fig 12 Overall water depths differences between original values and calibrated results using 5 observation points containing water depths and velocities

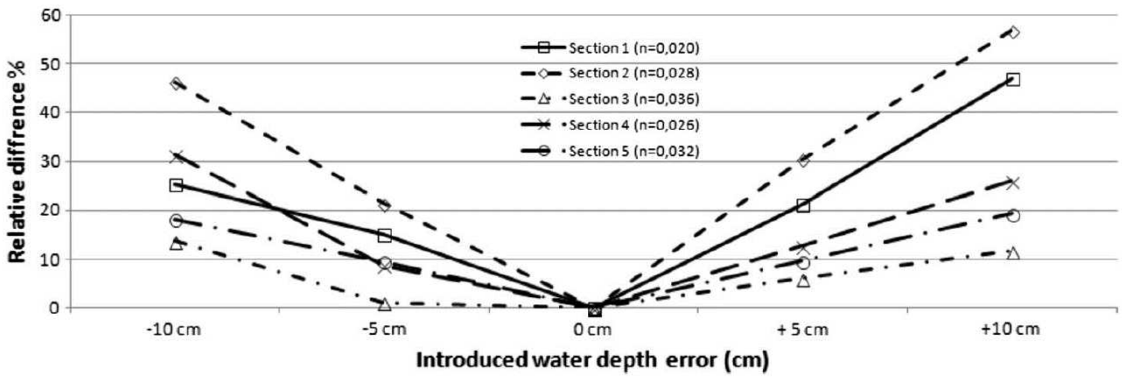


Fig. 13 Calibration sensitivity against measured water depths only

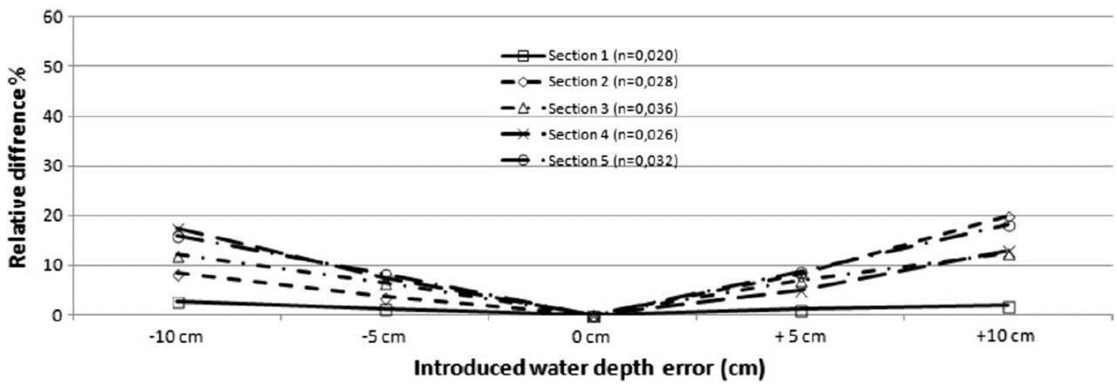


Fig. 14 Calibration sensitivity against measured water depths with additional information to the observation points

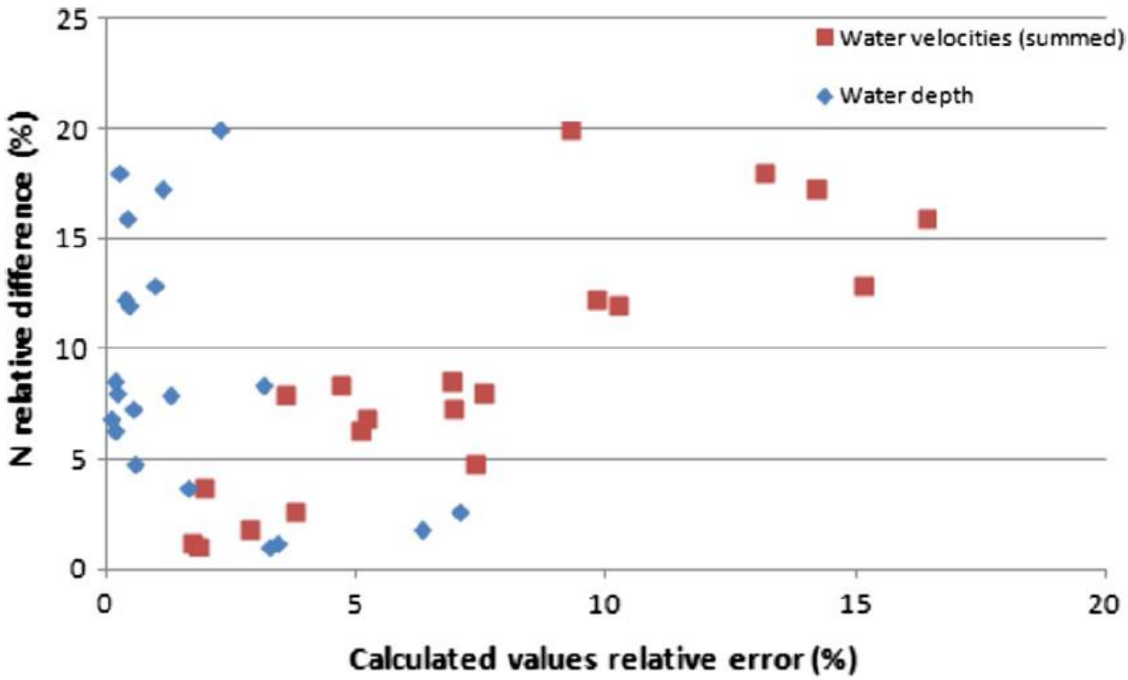


Fig 15 Calibration error distribution of calculated water depth error and the summed error of calculated water velocities

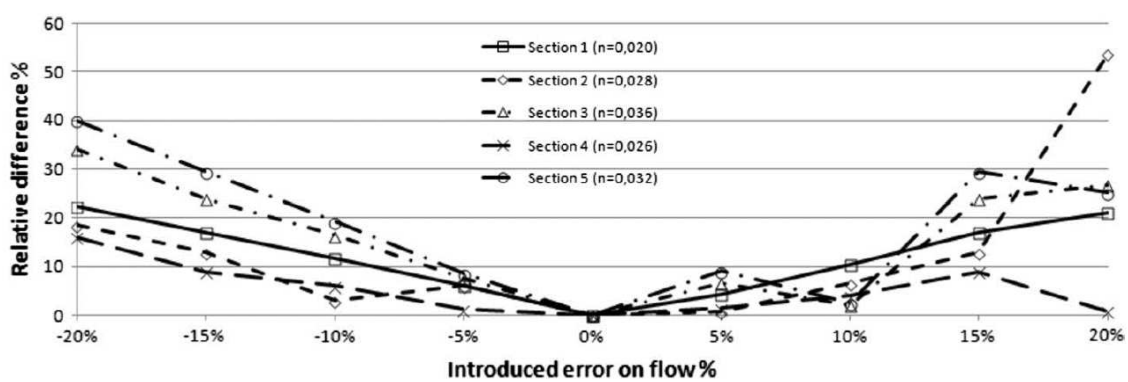


Fig. 16 Calibration sensitivity against model input flow using measured water depth and velocities

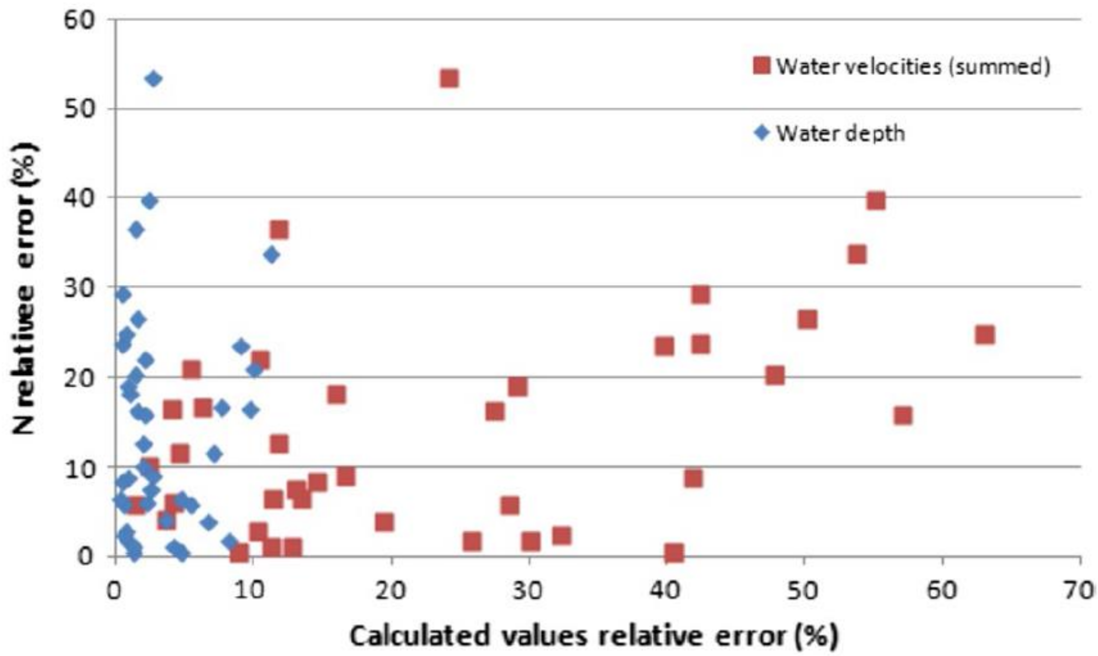


Fig 17 Calibration error distribution of calculated water depth error and the summed error of calculated water velocities