Performance of MOUSE UPDATE for level and flow forecasting in Urban Drainage Systems

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Abstract
MOUSE UPDATE is an additional package to MOUSE that enables generation of forecasts for urban drainage systems based on measured observations. In the investigated version, observed water levels are assimilated into specific nodes and the added/extracted water is distributed to the surrounding grid points as part of the standard hydrodynamic computations of MOUSE. This study evaluates and documents the performance of MOUSE UPDATE for water level and flow forecasting.

MOUSE UPDATE is implemented in models for a hypothetical and a real urban drainage system. Measured and synthetic water levels in combination with rain gauge input are used as basis for the evaluation. When compared to simulations without updating, the results show that it is possible to obtain an improvement in the 20 min forecast of the water level in an updated node and in the 3 hour forecast of flow through a downstream node.

The analysis indicates that MOUSE UPDATE produces better forecasts when implemented in a network with slow flow dynamics and with measurements from nodes that are located upstream and contribute significantly to the flow at the forecast location. This work represents the first openly available study on the performance of MOUSE UPDATE and provides a foundation for future developments and implementations.

INTRODUCTION
For any urban runoff model there will always be some deviations between the observed and simulated flows and water levels within the system. This can be due to groundwater infiltration, leaky pipes, poor precipitation measurements etc. or due to the simplifications made when making the model. For any online model that is used for decision making it is crucial to keep the model in touch with reality. For simple
models, this task would usually be performed by a classical data assimilation tool like the Kalman filter (Kalman, 1960). The nature of distributed, physically based urban runoff models like MOUSE, however, makes the implementation of classical data assimilation tools computationally burdensome.

MOUSE UPDATE is a pragmatic and ready-to-use tool that assimilates water level or flow measurements into the MOUSE model, thus ensuring that the simulations are in accordance with the available measurements. It should thereby result in an improvement in model performance. MOUSE UPDATE works by adding an additional flow to the model, which add or extracts the right amount of water to make the model value in the update location fit the measured value for each time step. MOUSE UPDATE has been applied by DHI in a few selected projects, but this study is the first publicly available study on the performance of MOUSE UPDATE. The article focuses on examples illustrating water level updating.

The article is divided into six parts: Introduction, Theory and Methods, Example A – Updating with MOUSE UPDATE, Example B – Forecasting with MOUSE UPDATE, Discussion and Conclusion. In Theory and Methods the theory behind how MOUSE UPDATE functions will be described along with the method used to generate forecast. Then two examples are used to illustrate how MOUSE UPDATE works and the effect that it has on the system. Example A is a hypothetical example, which illustrates how MOUSE UPDATE compensates for an inflow to the system that is not accounted for by the model or the applied boundary conditions. Example B is based on a MOUSE model of the city of Kolding, Denmark. There are a lot of flow and water level meters placed in Kolding, and the observations from eight of these meters have been used for updating. The measured outflow from Kolding is compared with the outflow from a simulation run with and without MOUSE UPDATE. The example also illustrates the forecast potential with MOUSE UPDATE. The article will be rounded off by a discussion of the parameters that affect the performance of MOUSE UPDATE and a conclusion on the results shown in the article.

**THEORY AND METHODS**

*How MOUSE UPDATE works*

The *MOUSE Pipe Flow Reference manual* (DHI, 2009) describes the computation technique applied in the MOUSE HD Engine for solving the Saint Venant Equations. The description explains how the computation uses a double sweep algorithm for solving two sets of equations set up as a “branch” matrix and a “nodal” matrix. In short the “branch” matrix is applied for computing flow and water levels in the pipes as function of the known water levels in the nodes at the end of each pipe. The “nodal” matrix is used for computing the water level in the nodes at the new time step. The coefficients in this matrix are set up based on the computed flow in the connected pipes and the external flow in or out of the node. For further details about the solution technique please refer to the manual (DHI, 2009) and its references.

To explain the method used in MOUSE UPDATE we will take a look at the conditions at the nodes when setting up the coefficients for the “nodal” matrix. Basically the continuity equation for the node is used for calculating the water level for the new time step based on the change in volume in the node, see Figure 1. This change in
volume is found by accumulating the computed flows in the connected pipes and the external flows over the time step. When the change in volume and the geometry of the node is known, the new water level in the node can be computed.

**Figure 1: Normal MOUSE HD node computation.**

The idea behind MOUSE UPDATE is that the new water level in the node is known from a measurement by a level sensor located in the node. This means that the before unknown parameter in the equation is now given by the data from the measurement provided as an input time series to the computation. The measured water level will in most cases deviate from the water level computed normally as described above.

In order to make the solution of the equations match the known measured water level an additional “correction” flow is introduced to the node, see Figure 2. This correction flow is now the unknown parameter in the computation while the water level is locked to follow the measured data. By reversing the equations locally it is now possible to make the equation provide the required correction flow as the computed result.

**Figure 2: MOUSE UPDATE node computation. In this example the MOUSE UPDATE correction flow subtract the volume of water necessary to lower the water level from the dotted blue to the red line.**
In other words the computed correction flow is representing the added or extracted water in the computation to make the resulting water level match the measured water level. The computed correction flow is fully reported to the results from the computation as a flow time series. The summary from the pipe flow computation also reports the accumulated volume of correction flow.

When using data from level sensors it is a common issue that the sensors may have a low level threshold, which is some distance above the bottom level at the location of the sensor. Using the water level signal lower than the threshold would introduce an error. The MOUSE UPDATE feature can be configured to work only when the applied water level signal is within a specified range. In addition to the reported correction flow, the results from the simulation also reports which periods during the simulation the update function was active. The MOUSE UPDATE function has a number of such features for detailed configuration.

This article and the work described have focused on using water level sensors for MOUSE UPDATE. The feature has also been implemented for using flow gauges as the sensor providing measured data for the update function. In this case the update function is applied to a computational grid point in the pipe where the flow gauge is located. Notice that the MOUSE Engine only computes flows in pipes and in special structures like pumps, weirs and orifices. The simulation never computes flows at nodes. To make the computation match the measured flow a correction flow is introduced that adds or extracts water from the pipe at the location of the flow gauge. In this case it is another set of equations which are reversed to make the update computation, but basically the principle is the same as when a water level sensor is applied. Application of MOUSE UPDATE with data from flow gauges has at present only been applied by DHI in selected projects.

The method applied in MOUSE UPDATE works very efficiently with respect to computational speed. The reason is that the correction to the simulation is done locally at the point where the sensor is located. Distributing the correction more widely over the model would require significantly more computational effort, which until now has not been possible to achieve in on-line applications.

It is the responsibility of the user to evaluate the result of applying MOUSE UPDATE with a specific model and simulation event. If the reported correction flows and volumes are large compared to the results from normal simulations it may be indications of poor calibration of the model or it could be errors in the applied measurement data. MOUSE UPDATE is not a short cut to bypass the work on creating a well calibrated model.

**Producing time series of forecasts**

When a model's upstream water levels are updated to more true-to-life values obtained from water level gauges the downstream flow simulation is expected to improve as well, as the effect of the update propagates down through the system due to the hydrodynamic processes. In the following examples MOUSE UPDATE is used to update the water levels in one or several nodes at a time. The effect of the update is examined by comparing measured downstream water level or flow with the corresponding water level or flow simulated with and without updating in upstream nodes. The forecast potential from updating is also examined. This is done by
comparing the simulation result $t_f$ minutes after updating has ceased with the simulation results from a model run completely without updating.

The $t_f$ minute forecasts shown are made using MOUSE UPDATE to assimilate water levels until time $t$, at which point MOUSE UPDATE is turned off and modelling is continued without updating until the time of forecast ($t + t_f$), see Figure 3. After the updating stops, the simulated values will converge towards the simulation run without updating. To generate e.g. a 60 minute forecast ($t_f=60$ min) a MOUSE UPDATE model is run with updating until time $t$, where after the model is run for 60 minutes more until time $t+60$ min. The result after 60 minutes is then part of the 60 minute forecast time series. This means that for each point in the forecast time series the model has to be run for the previous 60 minutes. So, to make a 60-minute forecast time series with a temporal resolution ($t_i$ on Figure 3) of 2 minutes, the computer workload increases with a factor of 30 compared to a single model run of the same period. In this article a 10 minute temporal discretisation (increment time) has been used when generating the forecast time series in order to reduce the computational burden.

**EXAMPLE A – A SIMPLE HYPOTHETICAL EXAMPLE OF UPDATING**

A simple system has been set up to illustrate the impact of using MOUSE UPDATE in a hypothetical system, see Figure 4. Artificial measurements are generated by running the model with an additional flow that represents water that is unaccounted for by the model. When running the model with MOUSE UPDATE this additional flow is not
included and it is then up to the update algorithm to compensate for the missing water.

The system consists of 6 nodes with a storage pipe section in the middle (Figure 4). The pipe diameters of the upstream pipe, storage pipe, pipe below the storage pipe and the downstream pipe are 1.5 m, 2 m, 0.35 m and 1 m, respectively. Two flow and water level meters are placed within the system: one at the outlet (O) and the other close to end of the storage pipe (S). The system has a total impermeable area of 25 hectares placed upstream and the water level in the outlet is set to 0.25 m. The storage pipe has a slope 0 ‰ where the rest of the pipes have a 2.5 ‰ slope.

Figure 4: Illustration of the model setup in MOUSE along with input and output locations.

To generate artificial observations at S and O a rain event from May 15th 2010 has been used along with an inserted flow located in the pipe downstream from the catchment, see Figure 4. The inserted flow represents water that is unaccounted for due to e.g. infiltration or deviations between actual and measured rainfall. The rain input and the additional inflow can be seen in Figure 5.

Figure 5: The inserted rain and the additional inflow inserted upstream from nodes S, also referred to as the unknown flow input.
These inputs generate a set of synthetic observations for node S and O, where the observations at node S are used for updating. MOUSE UPDATE is set to update the water level in node S only when the observation is above 3.45 m. The simulation result from updating is compared to the result from a simulation without MOUSE UPDATE.

The vertical dark blue lines in Figure 6 indicate whether MOUSE UPDATE is on or off – that is, whether the observed water level is above or below 3.45 m. The accumulated volume that is extracted and inserted by MOUSE UPDATE in node S can be seen in the uppermost figure in Figure 4, which shows a large amount of water being inserted into the model by MOUSE UPDATE. This is expected because the update algorithm has to compensate for the additional inflow representing unaccounted water (Figure 5). The correction flow (light blue curve) from MOUSE UPDATE can also be seen in the figure. It shows that there are large variations each time updating begins which is due to the fact that all compensating water inserted by MOUSE UPDATE is inserted during a single time step. This leads to some very sudden changes in water level which, besides a big initial peak, initiates some flow oscillations in the period right after the start of the update. This is also the explanation for the small accumulated volume of water that is extracted by MOUSE UPDATE.

Figure 6: Three graphs are joined to one is this figure. In the middle the water level in node S is shown, this is both the observed and simulated with and without MOUSE
**UPDATE. The rain input can also be seen.** On top the accumulated volumes inserted and extracted in node S by MOUSE UPDATE can be seen along with the correction flow (Cor. Q). On the bottom the flow into O can be seen for both the observation and the simulated with and without MOUSE UPDATE. In all of the three graphs it is indicated when MOUSE UPDATE is on or off by the dotted blue line.

The graph in the middle of Figure 6 shows the water level node S. It can be seen that the simulation with MOUSE UPDATE is equal to the measurements as long as the updating is on, whereas the water level slowly converges towards the simulation without update as soon as update is turned off.

The observed flow and water level at O along with the simulated flow with and without MOUSE UPDATE can also be seen in Figure 6, in the graph on the bottom. It shows that neither of the simulated flows result in a perfect match with the observed flow. This is due to MOUSE UPDATE only updating when the observed water level in node S is greater than 3.45 m. However, the simulation with MOUSE UPDATE is still far better than the simulation without.

**EXAMPLE B – REAL-TIME FORECASTING WITH MOUSE UPDATE**

This example describes the effect that updating in multiple upstream nodes has on the simulation result and forecast quality at the outlet. For this a MOUSE model of the urban drainage system in the city of Kolding, Denmark has been used. The example also examines the forecasting potential from updating when assuming a known rain input.

![Figure 7: Overview of the MOUSE model for Kolding. The red dots indicate where the observations from the six basins, two manholes and the outlet are located.](image)
The model setup is rather complex with 2303 nodes, 76 pumps and 94 weirs. Figure 7 shows where MOUSE UPDATE will be used in the model, along with the location of the main outlet in Kolding. It has been possible to acquire adequate water level observations from 6 basins and 2 manholes along with the flow observation from the outlet. Most of these meters are located close to a pump, which causes the dry weather flow to be dominated by frequent oscillations. MOUSE UPDATE has therefore been set to update only when the water level is higher than the maximum daily dry weather variation.

The event used is from December 2009 and is a very common event with a return period below 0.3 years for durations between 1 and 360 minutes. It lasts about a day and a half and has a rain depth of 18 mm. Figure 8 shows the observed and simulated flow at the outlet with and without updating in the upstream basins. It can be seen that neither of the two simulations manage to simulate the peak or tailing in the flow perfectly, but the simulation run with MOUSE UPDATE is notably closer to the observations than the simulation without MOUSE UPDATE.

![Figure 8: Observed flow at the outlet in Kolding on December 25th and 26th 2009 along with the simulate flow with (Update) and without (No Update) updating in the upstream basins. The rainfall intensity is also shown.](image)

As can be seen from Figure 8, the time period where the model run with MOUSE UPDATE gives a better result is between 11:00 on the 25th of December and 03:00 on the 26th of December. Figure 9 shows the 30 min and 3 hr forecast within this time period. The result for the 30 min forecast is very similar to the result for a simulation run with MOUSE UPDATE. The result for the 3 hr forecast is closer to the simulation run without MOUSE UPDATE until approximately 14:00 on the 25th, from then on and until around 03:00 on the 26th the result is very similar to the one achieved when using MOUSE UPDATE. This means that for almost a 12 hour period the 3 hr forecast will give results that are closer to the observations than a forecast made without using MOUSE UPDATE.
Figure 9: The simulated and observed flow at the outlet on December 25th and 26th 2009 along with the rain input. The simulated flow is with (Update) and without (No Update) MOUSE UPDATE. The green (top figure) and blue (bottom figure) squares represent the 30 min and 3 hr forecasts, respectively.

The results show that it was possible to improve the model simulation by using MOUSE UPDATE both during the peak and tailing of the flow. The improvement of the tailing of the flow was greater than during the peak. This is due to the fact that a lot of the fastest runoff runs directly to the WWTP without getting in contact with a basin with a water level meter, i.e. the fastest runoff processes are not included in the updating. Most likely both the peak and tailing could be further improved by updating in more nodes, but there is a limit to how much the description of the peak flow can be improved by this method. This is due to lack of basins near the outlet and because the greatest part of the impermeable area is close to the outlet. However, updating in more basins over the entire model area should improve the tailing in flow for the forecast time series.

DISCUSSION

MOUSE UPDATE is a fairly simple data assimilation tool, which strength first of all is in its ease-of-use and computational efficiency. Since MOUSE UPDATE defines water levels within the model directly from measured data, the uncertainties of the measurements are transferred to the model. This means that the measurements have to be of good quality and preferably the use of MOUSE UPDATE should be combined with an automated quality control of the measurements. Even when the measurements are perfect, MOUSE UPDATE should be used with care. If the relationship between flow and water level (Q/h-relation) at the update point is not exactly the same in reality as in the model, the consequence of using MOUSE UPDATE to control the water level will be the introduction of an erroneous flow into the
system. For this reason MOUSE UPDATE is most suited to be used to control water
levels in basins, whereas the uncertain flow regime in ordinary manholes most likely
would cause problems if updating were attempted in these. Furthermore, the fact
that basins store relatively large amount of water and empty relatively slowly makes
the effect of updating in these significant when producing forecasts.

The MOUSE UPDATE feature is intended for improving accuracy of model simulations
in on-line applications. The success of the method is depending on the quality of the
model, on the quality of the data from the applied measurement sensors and on the
characteristics of the system considered. The method introduces changes to the
calculations, but it is not done as a “black box” function since all modifications are
reported to the results as correction flows and accumulated volumes. The method can
be described relatively simple as in this article despite the real implementation and
handling of the equations is more complex. The method does not introduce
mysterious water to the simulation. The correction flow is the means of compensating
the deviation between normally computed results and the actual real measured data.

CONCLUSION

MOUSE UPDATE is a simple ready-to-use extra module to MOUSE that has the
potential to integrate water level measurements into the MOUSE HD model. Based on
the results from this article it can be concluded that MOUSE UPDATE improves
simulation results for both the updated node and downstream nodes. The
improvements have not been quantified statistically in this article and they will
without doubt vary from case to case. The results from Kolding showed the improved
forecasting potential when using MOUSE UPDATE on water levels in basins.
Simulations of the downstream flow to the treatment plant were significantly
improved and even a 3 hour forecast based on MOUSE UPDATE resulted in significant
better simulation of the flow than a model without updating. MOUSE UPDATE is no
magic tool that removes the necessity of a thorough model calibration but it is a
pragmatic tool that can help to compensate for the always existing deviations between
model simulations and measured data.

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