Linking of 2D and Pipe hydraulic models at fine spatial scales.

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Abstract

Linking of two-dimensional overland flow hydraulic models with one-dimensional storm water pipe models at very fine resolution is becoming a standard approach for urban flood investigations. This paper describes the application of such an approach to a variety of small, complex urbanised catchments in Australia and New Zealand. A benefit of this approach is that previously hidden information in terms of secondary flow paths and cross-flows become apparent, an outcome that is not possible with traditional 1D modelling tools. Generation of flood risk mapping is much simpler through the use of direct GIS interfaces to the model result files, making the modelling and presentation process much more transparent. The paper will describe the application of the models, the calibration approach and some specialised modelling techniques when working at such fine spatial resolution in urban environments.

Keywords

Stormwater Modelling, Two-Dimensional Flooding, Integrated Modelling Solutions

INTRODUCTION

Stormwater Modelling has traditionally relied on a delineation of hydrology and hydraulic components, where the catchments contributing flow are simulated in a lumped conceptual hydrological tool, and the channels and flood flows are simulated in a separate hydraulic tool. This approach is well suited to rural catchments with long times of concentration and where the area of interest has a large catchment above it and flow paths are reasonably well defined. In small urban catchments however the entire catchment is often drained by a complex terrain with many flow paths and the catchment is interwoven with hydraulic elements so that they cannot in a practical sense be separated. The combination of detailed terrain and linked pipe and 2D overland models means that these urban catchments can now be simulated in a single combined hydraulic and hydrologic solution, resulting in a level of certainty and accuracy that offers substantial improvement over earlier approaches.

Typically, the questions to be answered in urban flood studies are:

- Where in the catchment does significant flooding start to occur?
- What is the capacity of the stormwater asset? (Is there sufficient inlet capacity? Are the pipes large enough?)
- Are all the potential overland flow paths serviced by the stormwater asset?
- Where are the significant overland flow paths?
- Do the overland flow paths change in larger storm events?

All locations of flooding problems over the full range of risk levels may not be known in advance because the length of record is small and movements in population mean that knowledge may have been lost. Further, different flow paths will activate at different flooding frequencies which means that observed flood behaviour does not always cover the full range of potential scenarios. The linked 1D/2D approach is able to provide answers to many of these questions because it simulates down to the smallest elements of the catchment and makes no prior judgements as to the location of problem areas.

THE CONCEPTUAL MODEL

MIKE STORM (DHI, 2004) is link-node pipe and channel model which is suitable for application to standard stormwater networks using the traditional approach, and for the sub-surface component of the urban drainage network when using the linked 1D/2D approach.

The 2D overland flow simulation engine can either be the MIKE SHE (DHI, 2004) or MIKE 21 (DHI, 2004) depending on the type of problem to be analysed.

MIKE SHE is a deterministic multi-layer catchment model which simulates the following processes in a 2D/3D framework:

- Overland Flow with an unsteady non-uniform 2D finite difference diffusive waver solver. Overland flow interacts with the unsaturated zone, and saturated groundwater zone.
- Spatially-Variable Precipitation, Infiltration and Evapotranspiration
- Two-Layer Water Balance in the Unsaturated Zone
- Groundwater Flow

MIKE SHE is therefore most suited to partly urbanized catchments with no downstream backwater effects and where there are groundwater issues which create baseflow in the stormwater networks.

MIKE 21 is a fully dynamic 2D hydraulic solver that can accommodate backwater effects and fine-temporal-scale hydraulic behavior. MIKE-21 is therefore more suited to complex overland flow problem areas for example low-lying coastal urban areas.

The connection between the surface and pipe network is via a weir/orifice combination which represents the pit network. The catchment model and the pipe model are executed together and dynamically link flows on a time step basis. Backwater effects and reversing flows are accommodated in the linking, so that if the pipe capacity is exceeded in the pipe model, then the surface model will route the flows overland and cause surface flooding if channel or overland flow path capacities are insufficient.

Catchment rainfall runoff and overland flow accumulation is determined by applying rainfall directly to the 2D digital elevation model of the catchment surface. The surface model allows a distributed, physically based approach to rainfall runoff, with rainfall time series applied directly to a two dimensional grid representation of the catchment surface. Rainfall losses are accounted for either by using the infiltration processes in the MIKE SHE model or by an initial and continuing loss technique approach when using the MIKE-21 solver.

An important aspect of model setup is that detailed information around each pit is necessary in order to route the flows correctly. This requires that each pit and it's detailed configuration be inspected and measured as part of the study so that the details can be incorporated into the model. LIDAR-generated terrains can be provided either with buildings included or removed, which means that the sensitivity of the results to obstructions by buildings can be investigated if required, with little effort in model setup time and cost.

CASE STUDY 1 - AUCKLAND NEW ZEALAND

A catchment was analysed using the linked 1D/2D approach which had previously been modeled using a traditional hydrologic/hydraulic solver. The earlier study had applied lumped Kinematic Wave Hydrological catchments combined with a 2-layer link-node hydraulic model to route overland flows through cross-sections and subsurface flows in 1D pipes. For the purposed of this discussion, this model will be referred to as a 'Standard 1D model". For this study of the linked

2D/1D approach, , the MIKE SHE surface option was chosen because the catchment has no tailwater issues. Not all the pits were individually modeled in the catchment because a decision had been made in the earlier study regarding a tradeoff in schematizing the 1D model in relation to the level of detail required to meet the overall objectives of flood mapping. Areas of potential flood issues had been pre-determined and the model schematized to cover those areas.

Ground Surface Contours of the trial area were first processed into a Digital Elevation Model on a 5m grid to create the catchment surface. The base data for the DEM development was 2m photogrammetry-based contours which were processed into a DEM. While not utilizing the potential of a LIDAR-based terrain, the work was undertaken to determine if the 1D/2D approach could produce similar or better results with equivalent effort.

The original pit and pipe model was simplified by removing all the overland flow links and removing all the surface storage elements. This reduced the model from 112 catchments, 412 nodes, 206 weirs and 419 links to a model of 216 nodes and 227 links, roughly half the size and with much less complexity. All catchment runoff processes and surface flow processes were replaced with the single integrated 2D surface model. The 2D model does not require any sub-catchment delineation except for the outer catchment boundary, this reducing the time taken to develop the basic model. A single rainfall event in June 2000 was selected for calibration. This event was approximately a 1 in 10 year event.

Calibration

Figure 1 shows the calibration results for the June 2000 event. The standard 1D model results show an under-prediction of the first peak and a significant over-prediction of the main peak. The coupled model shows a slight under-prediction of the first peak and a significant under-prediction of the main peak. However the long period of baseflow could be taken into account in evaluating the performance of the models, in which case the 2D model would give results which are much closer to the measured data. This modelling study did not couple groundwater effects to the pipe network, so the baseflow was under-predicted by the modelling.

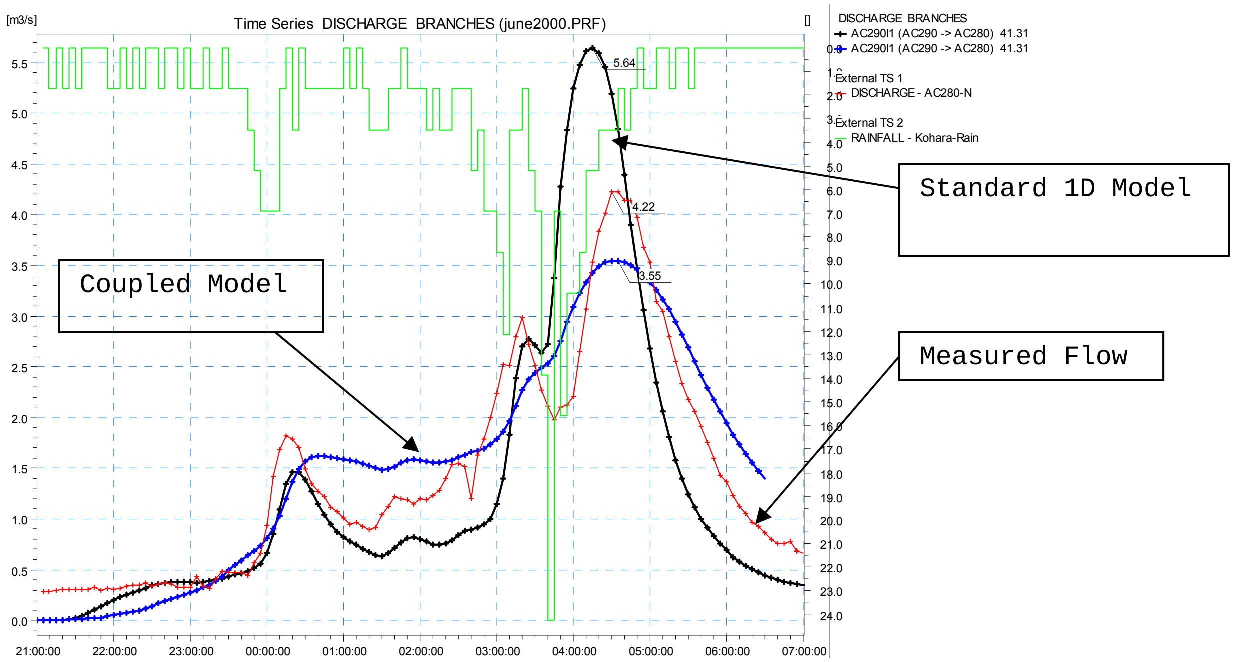

Figure 1:June 2000 Event Calibration to Auckland trial area

The 2D model does not fall away in flow between the first and second peaks as is simulated in the 1D model and is shown in the data. This is explained by realizing that the pipe network in the coupled model does not extend to all of the pits in the drainage area, and therefore the runoff must travel overland to reach the pits before it can enter the pipe network. This means that the 2D model has more delay and storage in the routing than the 1D model, and would explain the reason why the 2D model does not match the measured responsiveness of the flows.

An option in the MIKE SHE 2D model allows for ‘paved areas’ to be directly connected to pipe links with no hydraulic routing. This method of analysis allows a catchment area to be analysed for ‘residual flooding’ on the assumption that all pits are fully operational (i.e. no blockages) and there is no restriction in the pipe networks (i.e. the pipes are assumed to be able to carry all the flow that reaches the pits). The GIS layers provided had the locations of all pits in the catchment, and these were registered onto the 2D model. Figure 2 shows a comparison of the measured flow and the summation of catchment inflows which could potentially be carried by the pipe network.

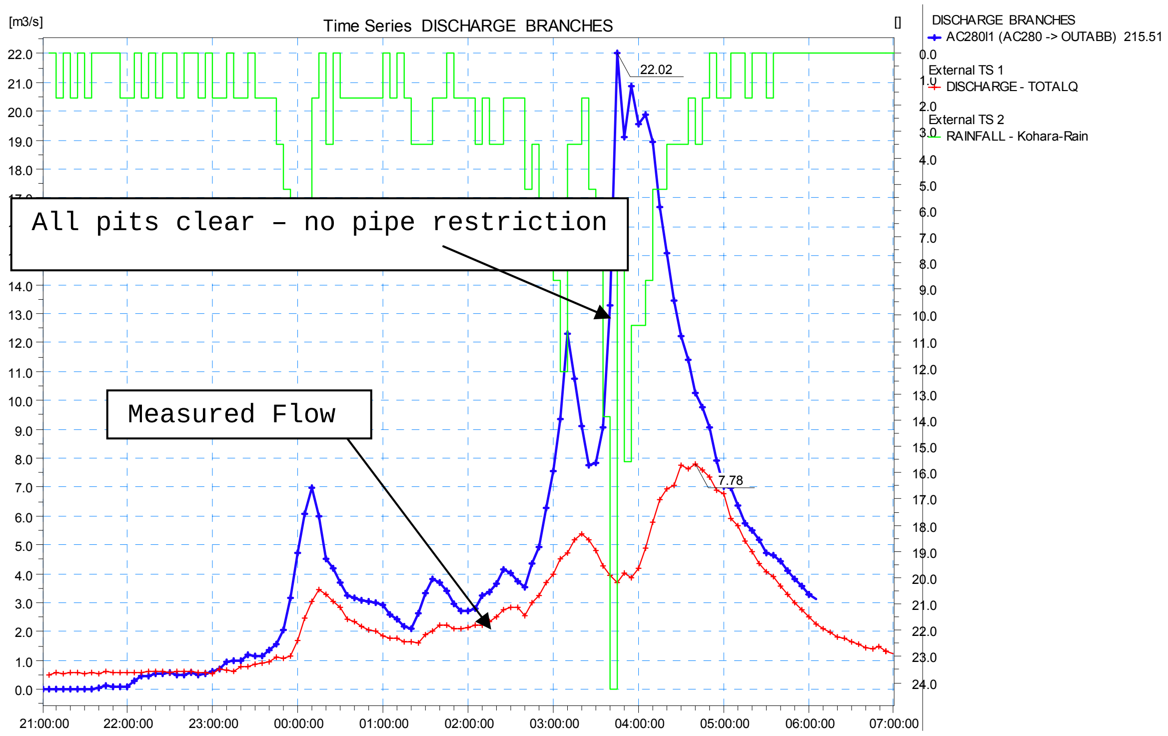

Figure 2: Simulated June 2000 Event with all pits unblocked and modeled – no pipe restrictions

The results show that the shape of response of the model is very good compared to the measured flow and the rainfall. The run also shows that the ‘no pipe restriction’ flow is much greater than has been measured by the gauge, and suggests that the pipe network is not able to carry the ‘no pipe restriction’ flows. The issues in the catchment are therefore a combination of insufficient pipe capacity and a lack of pits to capture the flows.

CASE 2 – AUSTRALIAN COASTAL CATCHMENT

The integrated 1D/2D approach was applied to a 210 hectare catchment in the Upper Middle Harbour catchment of Sydney. The catchment is a moderately steep, urbanised catchment. It is characterised by predominantly low-medium density urban development. Most of the catchment is serviced by formalised kerb and gutter connecting to a sub-surface piped stormwater system. In the lower parts of the study area, the sub-surface piped system drains to open channels. Many reaches of these two channels have been altered from their natural state by concrete or block lining. The open channels run through narrow drainage easements which are restricted by the close proximity of residential properties whose boundary fences restrict flows in some instances. An overview of the study area and properties that have reported flooding issues is shown in Figure 3.

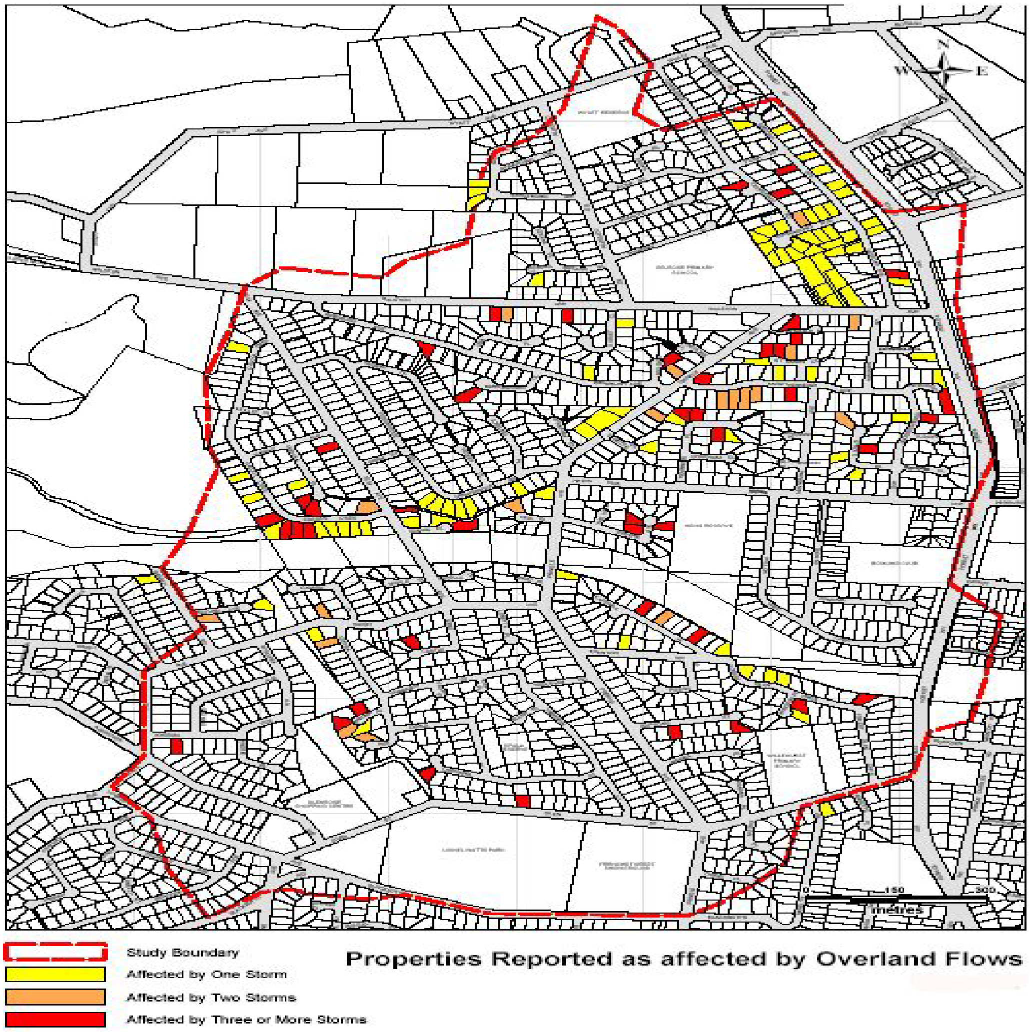

Figure 3: Overview of the Catchment and flood-affected properties

MODEL DEVELOPMENT

Model development involved the independent development of a DEM of the catchment surface and the compilation of the sub-surface stormwater pipe network. These two parallel systems were then linked in via the stormwater pits network. Pit lintel lengths and geometries were surveyed individually.

A surface DEM was created using 0.5m photogrammetric contours and available ground survey data, with the survey data taking precedence over the contours. The surface DEM was developed to a 3m grid resolution, using an automated, GIS based technique to collate and manipulate the available ground survey data into 2D surfaces quickly and efficiently. A grid on this resolution covering the catchment has approximately 366,500 computational grid points. Polygons representing building footprints were digitised using the available digital aerial photography. A representation of the buildings was then extruded in the DEM based on these polygons.

A key issue in model development is to ensure that the elevation of the 2D terrain model is the same as the elevation of the node representing the pit in the 1D pipe model. Even at small spatial scales, a 3m error in the plan coordinates of the pit may move the node to the adjacent gridcell in the 2D model and therefore it may be either too low (in which case it attracts too much water) or else it will be proud of the surface and will not allow water to enter the pit. Although pre-processors help with this issue greatly, it is an element of fine detail that needs to be carefully assessed for each pit.

Surcharges, pit inlet capacities and pit bypasses are estimated automatically by the linked 2D system because the entire network is analysed as a single hydrologic/hydraulic unit. Overland flow paths appear according to the proper accumulation of flow and channel capacity rather than needing to be pre-defined based on resident surveys.

A real advantage of this method is to use the model as an initial rapid assessment tool to define the location of possible flood pathways and the target the data collection process to these areas. The 2D model surface modelling approach also eliminates issues with additional overland flows paths that may occur for more extreme events that can potentially be underestimated or missed entirely using a 1D approach.

MODEL CALIBRATION

Calibration of the model was an iterative process, which followed the steps listed below:

1. Develop rainfall hydrographs for calibration event. Apply rainfalls to entire catchment, removing losses. Compare overall hydrographs to regional methods at outlet, adjust losses to match expected flows.
2. Compare modelled peak water levels to historical peak water levels.
3. Adjust surface roughness, pipe roughness and pit inlet parameters to improve estimates an return to step 2.

In practice, pipe roughnesses have a relatively minor affect, and it is the pit inlet coefficients which control the amount of water that can enter the sub-surface system. However when there is significant surface flooding, the pipe network is completely filled and overland flow roughness is the only calibration parameter available. So in effect, apart from adjusting rainfall losses in the lower frequency events to obtain the expected volume of runoff, there is relatively little calibration effort required. More likely, variations in water levels are due to local issues such as fences and obstructions.

RESULTS

A comparison of the modelled and recorded peak water levels at 7 locations is presented in Table 1.

Address	DEM (m AHD)	Flood Level (m AHD)	Depth (m)	Peak Water Level (mAHD)	diff
Location 1	146.47	147.50	1.20	147.67	0.17
Location 2	145.88	146.40	0.39	146.27	-0.13
Location 3	143.84	144.07	0.37	144.21	0.14
Location 4	149.76	150.20	0.69	150.45	0.25
Location 5	149.90	150.70	0.77	150.67	-0.03
Location 6	146.58	146.80	0.23	146.81	0.01
Location 7	150.88	151.00	0.57	151.45	0.45

Table 1:Comparison of Modelled and Recorded Peak Water Levels

The model results closely match the recorded levels in most instances. In locations where the peak water level was not matched closely, detailed site inspections revealed influence by local hydraulic features that were not represented at the 3m grid. The influence of these local features such as fences blocked with debris etc are difficult to represent even at a 3m grid.

The model outputs were also verified against reported overland flow paths in other areas to ensure that the flow patterns being generated by the model generally matched those reported as flooded by residents.

RESULTS PRESENTATION

Presentation of results from the 2D overland flow model requires no processing, as the result files are directly loadable into GIS without any manipulation as shown in figure 4.

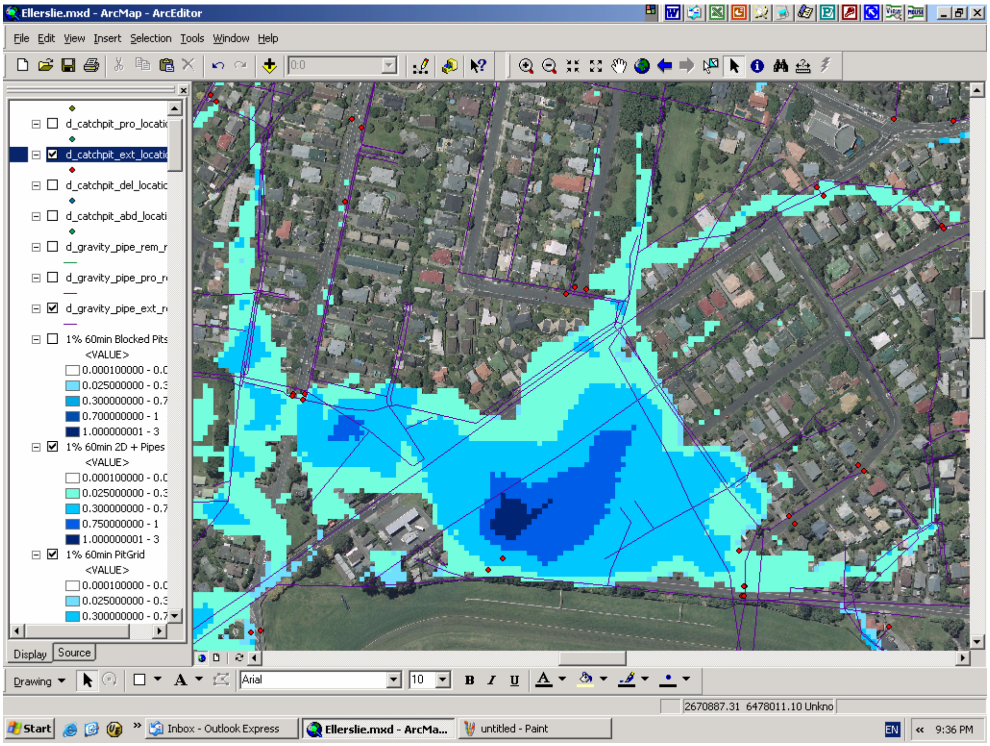

Figure 4. Flood Inundation Map from 2D overland model.

A wide variety of spatial information is generated including:

- Flood Depths
- Flood Elevations
- Velocities
- Hazards
- Any other metric through GIS processing of information – may include non-flooding information incorporated into the GIS.

These two studies utilized existing ground survey supplemented with detailed information at pits and at known benchmarks. Recent advances in LIDAR (LIght Detection And Ranging) has resulted in accurate ground levels over wide areas to be obtainable at reasonable costs. This technique has been applied in other linked 1D/2D flooding studies with very good results.

CONCLUSIONS

The spatially linked 2D overland and 1D pipe modelling approach brings modelling much closer to a physical representation of catchment behaviour than has been previously possible. Opportunities to discover new or hidden information about flow paths and high risk areas are created through not needing to make prior judgements about flow paths and directions. The applications presented have demonstrated that the approach is able to represent the behaviour of the catchment with minimal calibration, and effectively reduces model setup-time and interpretation.

The combination of 2D catchment modelling linked with 1D pipe modelling opens up an entirely new physically-based approach to urban stormwater applications. This level of integration between direct model output and readily useable information creates opportunities for substantial changes in the way information is used and transmitted both within an organization and with the community that it serves.

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