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Recent Advancements and a Preview of Future Directions for the EPA Stormwater Management Model

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United States Environmental Protection Agency

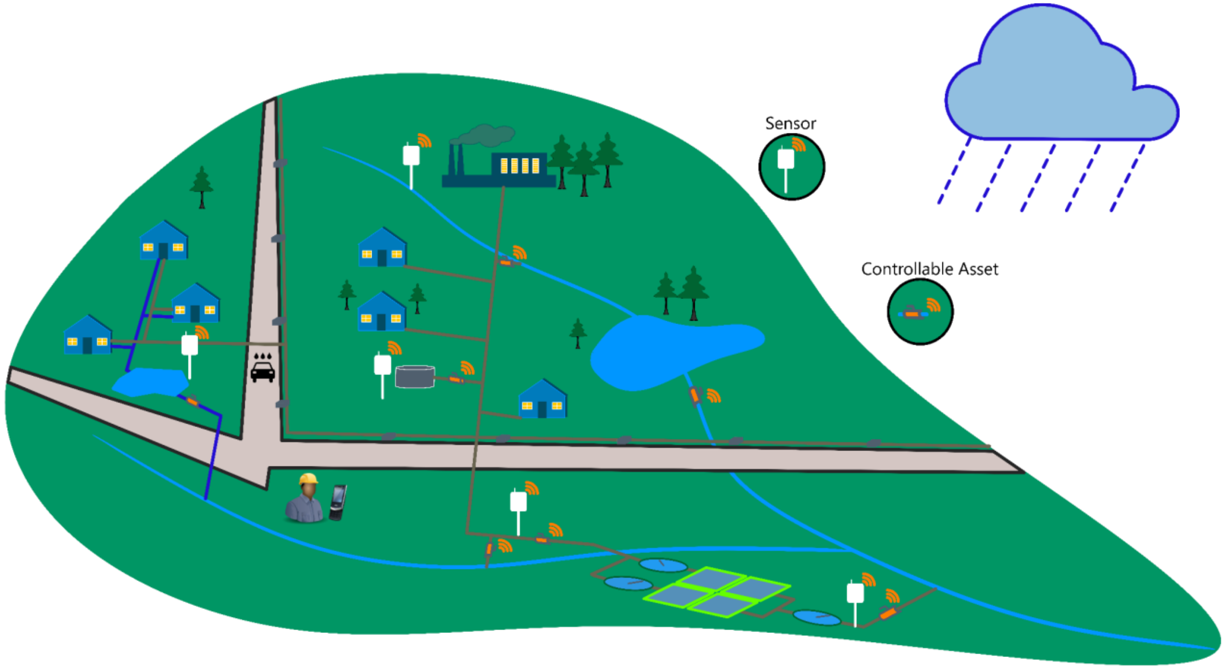
EPA Administrator's Powering the Great American Comeback initiative

- Pillar 1: Clean air, land, and water for every American
- Pillar 2: Restore American energy dominance
- Pillar 3: Permitting reform, cooperative federalism, and cross-agency partnership
- Pillar 4: Make the United States the artificial intelligence capital of the world
- Pillar 5: Protecting and bringing back American auto jobs

- EPA's development of SWMM aligns with this initiative
  - SWMM is the go-to tool for engineers and utilities for stormwater infrastructure planning and design towards improved water quality and volume control outcomes to comply with various statutes (e.g., CWA)
  - SWMM's development is also done in an open and collaborative manner with insights from consultants, academics, and utilities at various fora
  - We are increasingly looking at ways in which we can use AI/machine learning and data driven approaches in general can be used improve SWMM and stormwater management more broadly

Towards the Intelligent Collection Systems of the Future

- Cyber-physical collection systems with sensors and automatically actuated infrastructure (i.e., gates, pumps, etc.)



- Virtual, high fidelity, and realtime models of collection systems — digital twins
- Predict model state and evolution over future time horizons with different operational paradigms
- Optimization algorithms for infrastructure design and decision support

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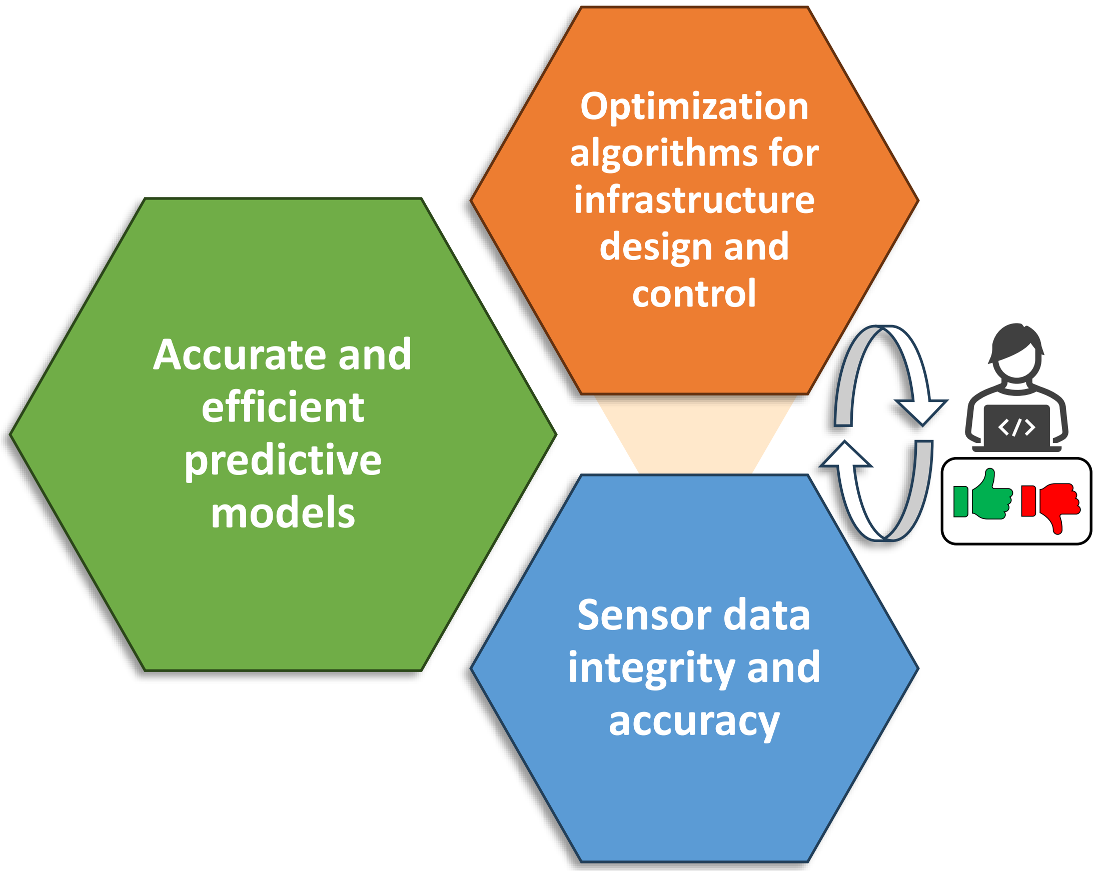
Components of Digital Twins for Collection Systems



- Research Goals:
  - Use multiple lines of evidence/understanding uncertainty from an ensemble of models including SWMM to support near real time decision making and for long-term planning
  - Use models to identify and address sensor data integrity and accuracy issues
  - Optimization and control algorithms for infrastructure sizing, placement, and coordinated operations
- SWMM, Artificial intelligence/machine learning/data-driven approaches in general have roles in all three areas

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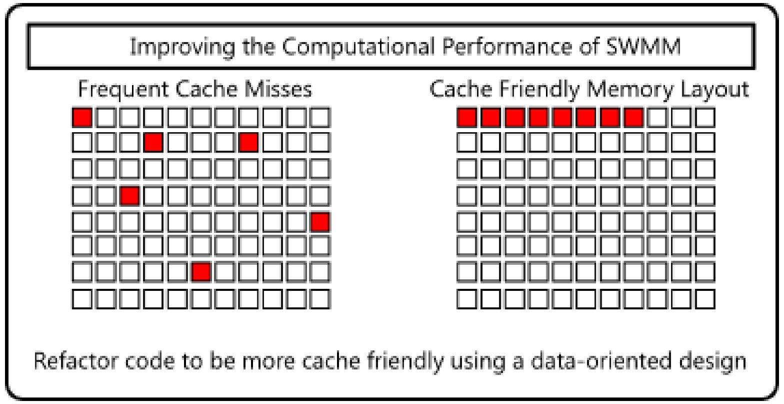
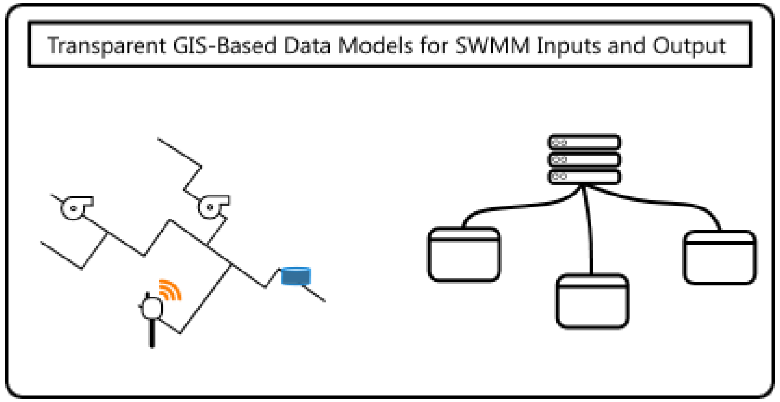
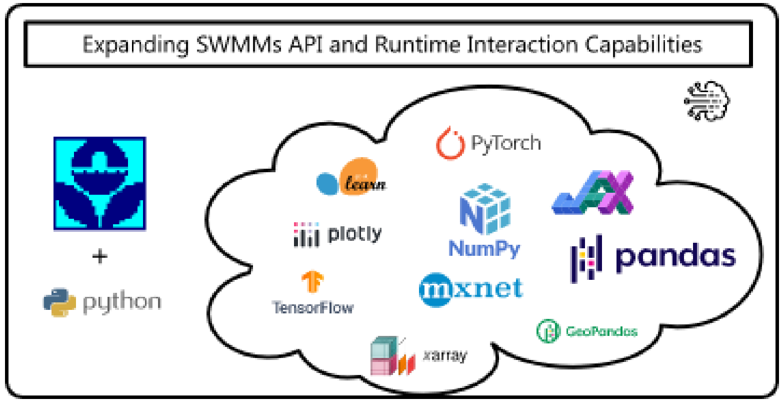
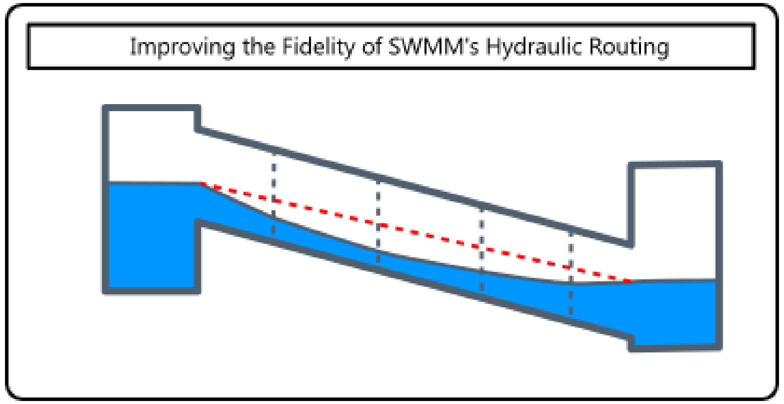
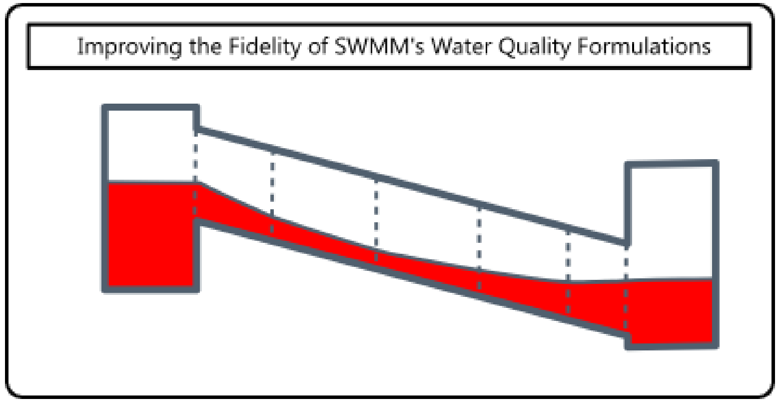
Advancing SWMM to Support Intelligent Collection System Development

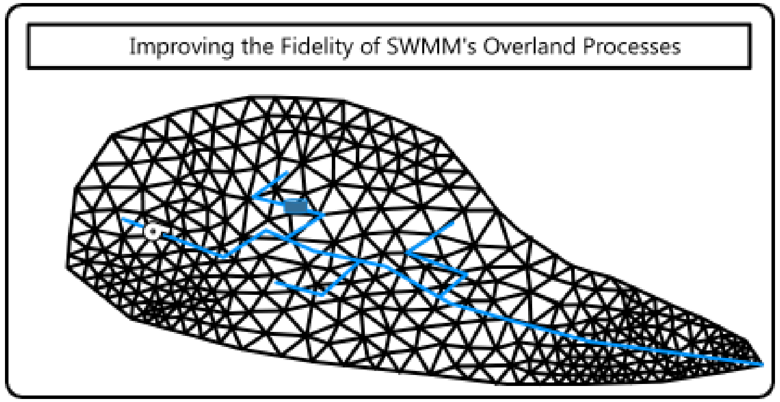












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First things first: Version 5.3.0 Release

- Targeting end of year for release; later than originally anticipated
- Because of the minor version number bump, we have expanded list of bugs and items we are addressing
- Items being addressed:
  - Multi-platform support for the engine (Windows, Linux, MacOS)
  - Expanded unit and regression testing
  - Expanded application programming interface (API)
  - Official EPA python bindings
  - Consolidating documentation and providing live web (unofficial) versions of the manuals and source documentation
  - Improved IO handling

Labels | Milestones | Edit milestone | New issue

v5.3.0

Due by April 01, 2025 27% complete

We are having to extend the release date on this to accommodate EPA's internal review process.

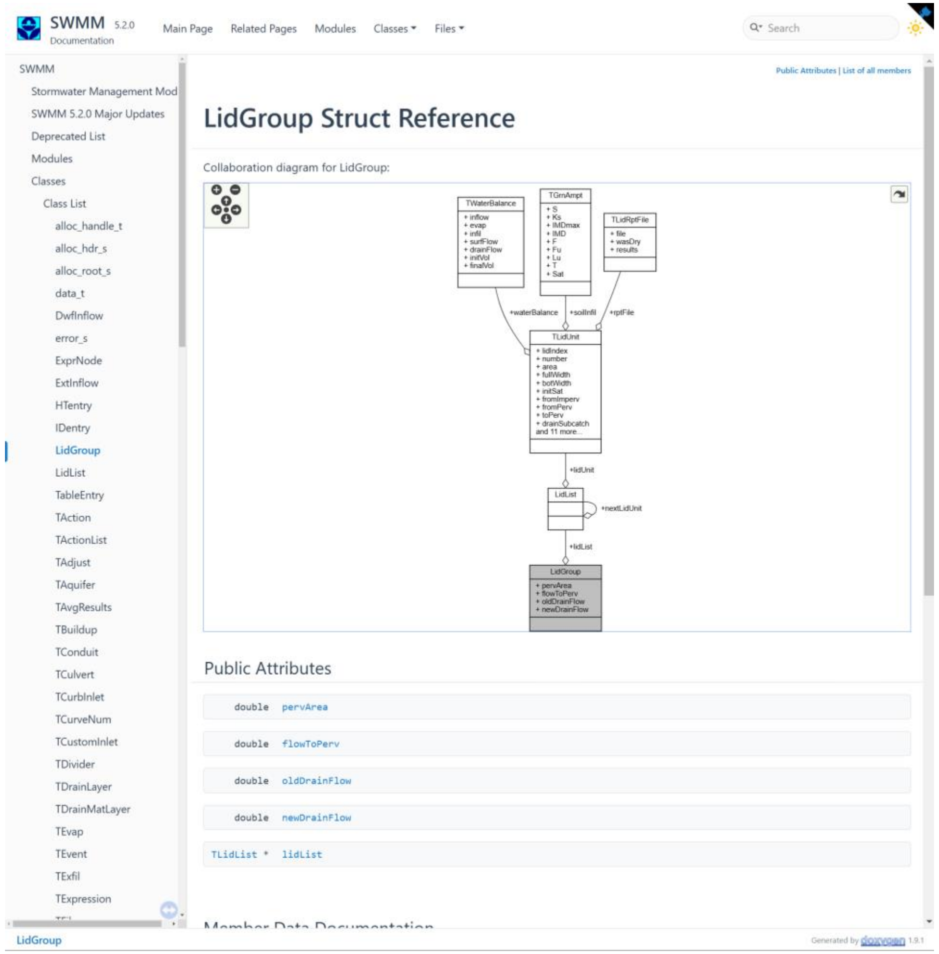
24 Open ✓ 9 Closed

- Constants precision nits `addressed` `enhancement` — #70 opened on Mar 19, 2021 by MitchHeineman — 1 — 6
- Configure transparent and fast build of Boost Test Libraries — #182 opened on Jul 12, 2024 by cbuahin — 3
- High continuity error, critical elements, and flow instability tables display `enhancement` — #32 opened on Jan 28, 2020 by MitchHeineman — 2
- Allow multiple outfalls to be listed in a single timeseries file `enhancement` — #31 opened on Jan 28, 2020 by MitchHeineman — 6
- Experimental build for linux and macos `enhancement` — #131 opened on Jul 7, 2023 by cbuahin — 2
- Incorrect depression units in User Manual for Streets/Inlets `documentation_error` — #111 opened on May 23, 2023 by jlhomme
- Incorrect Geometry for Custom Elliptical Pipes `bug` — #144 opened on Sep 12, 2023 by LRossman — 1 — 22
- Unit Hydrograph ALL months functionality `enhancement` — #18 opened on Apr 4, 2019 by MitchHeineman
- SWMM 5.2 not issuing warnings/errors for incompatible pairs of conduit cross-section and inlet types `enhancement` — #104 opened on Jan 24, 2023 by dapaez270
- Documentation issues `documentation_error` — #96 opened on Nov 17, 2022 by MitchHeineman — 4
- Resolve errors in specification of lookup tables for masonry cross-sectional shapes `bug` `enhancement` — #160 opened on Jan 26, 2024 by cbuahin
- Area for storage exfiltration `bug` `enhancement` — #167 opened on Mar 11, 2024 by NandanaPerera
- Support for 'outflow' value in getNodeValue method `enhancement` — #168 opened on Mar 19, 2024 by jubilee2 — 1 — 3
- Expand SWMM API to Support Other Objects `enhancement` — #163 opened on Feb 20, 2024 by cbuahin
- Expand unit test coverage and expand regression testing `enhancement` — #162 opened on Feb 12, 2024 by cbuahin — 2
- Code documentation following doxygen convention `enhancement` — #180 opened on Jun 13, 2024 by cbuahin — 1
- Code for inlets does not account for submergence `enhancement` — #139 opened on Aug 23, 2023 by awh142857 — 1 — 19
- Migrate API Guide from CHM to markdown `enhancement` — #177 opened on May 13, 2024 by michaeltryby
- Fix code documentation regarding generation of rainfall interface file formats `documentation_error` — #186 opened on Jul 25, 2024 by cbuahin

https://github.com/USEPA/Stormwater-Management-Model/milestone/2

Consolidating Documentation and Improving Access (v5.3.0 release)

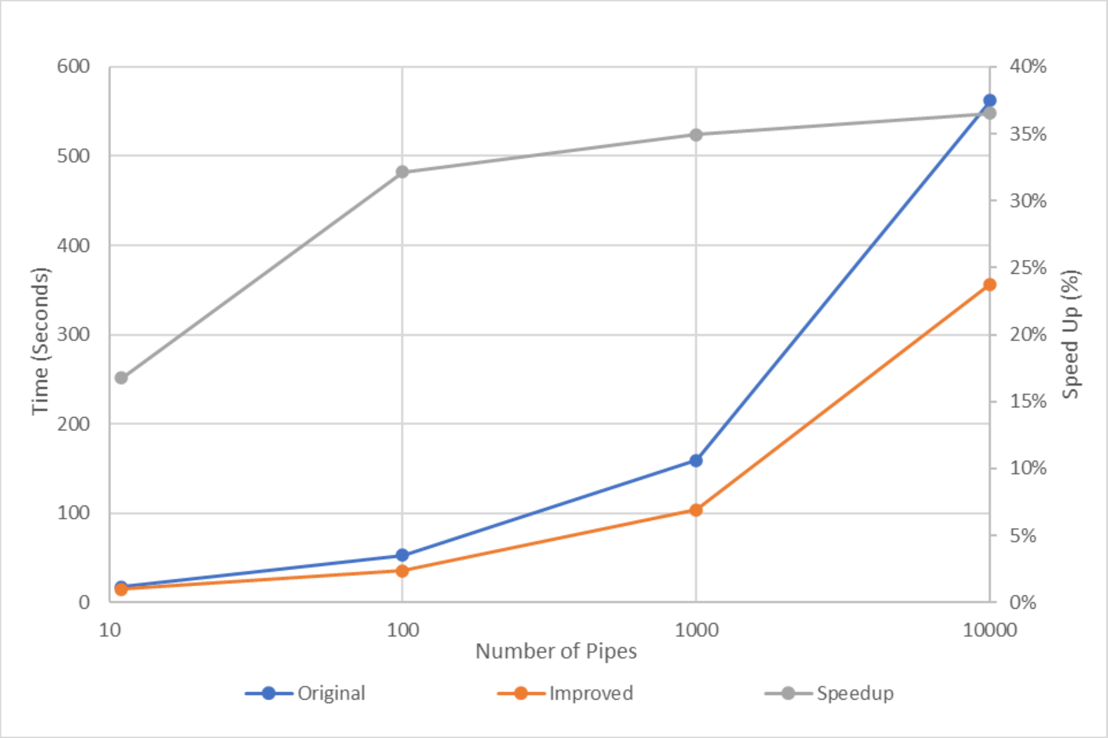
- Consolidation of official SWMM technical and application manuals
  - Integration of errata
  - Fixing other errors
- Frequently updated developer oriented and GitHub hosted web versions of manuals (with latest but ***unofficial/uncleared*** fixes of errors)
- Browsable source code with UML relationships and call graphs



https://usepa.github.io/Stormwater-Management-Model

Computational Improvements (v5.4.0/v6.0.0)

- Vectorizing SWMM code and making it "cache friendly":
  - Reconfiguring data layout in memory
  - Removing if-else statements from inner loops
- In memory time series data caching
- Object oriented and thread safe
- Component-based modeling
  - https://github.com/HydroCouple/HydroCouple
- Promising results!
- Longer term:
  - Exploration of hardware acceleration and potentially, distributed computing will be useful
  - Other numerical solution techniques



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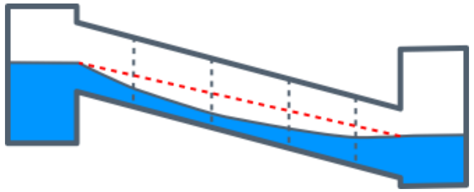
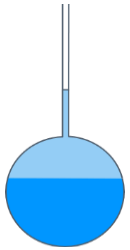
Improving the Degree of Fidelity of Hydraulic Routing and Pollutant Fate and Transport (v5.4.0/v6.0.0)

- Virtual non-storage junctions for explicit momentum conservation to resolve highly dynamic flows
- New numerical solvers for 1d routing:
  - Experimenting with semi-discrete finite volume option
    - Discretize in space; continuous in time
- Full advective-reactive formulation for pollutants and heat transport
- Alternatives/improvements to the Preissmann Slot approximation to handle transitions from open channel to pressurized flow
  - Dynamic Preissmann Slot (SWMM 5+)
    - Sharior, S., Hodges, B.R., Vasconcelos, J.G., 2023. Generalized, Dynamic, and Transient-Storage Form of the Preissmann Slot. J. Hydraul. Eng. 149, 04023046. https://doi.org/10.1061/JHEND8.HYENG-13609

Sub-grid discretization to resolving flow dynamics



Dynamic Preissmann Slot



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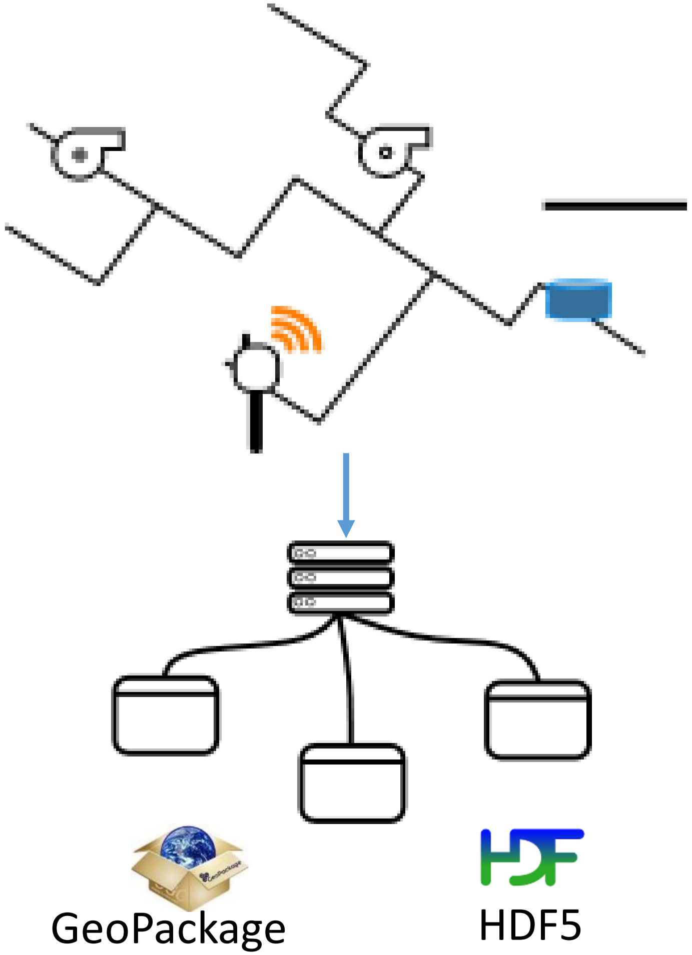
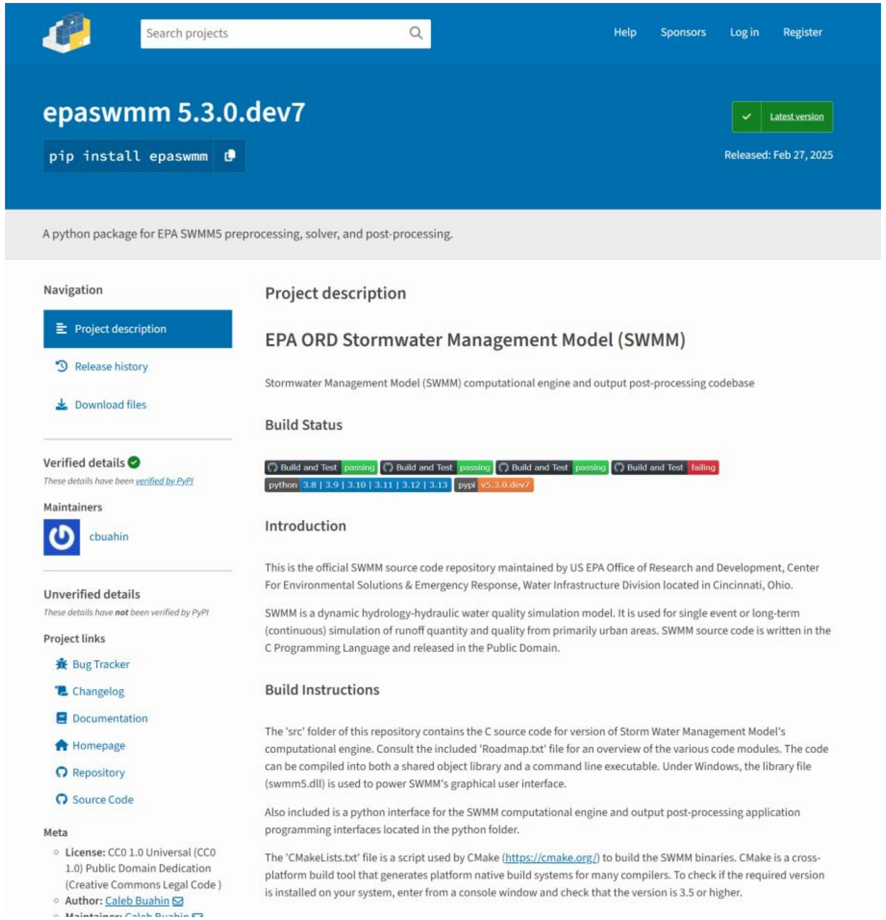
Data Inputs and Outputs

- Support for CSV (v5.3.0)
  - Multiple time series in a single file
  - Data caching
- NetCDF/HDF5 support for outputs and hotstart files (v5.4.0/v6.0.0)
- Support for model domain and delineation using standard GIS datasets (v6.0.0)
- Model forcing using remotely sensed or model derived gridded data products (v6.0.0)



Official EPA Low Level Python Bindings (Alpha Testing)

- An official transparent, low level, and efficient python bindings for the SWMM engine and output file API is now being tested:
  - Supports unit and regression testing
  - Multi-species reactions
  - Parameter estimation, sensitivity analysis and uncertainty assessment
  - For various applications in the smart/intelligent water systems area:
    - Multi-objective Optimization
    - Real time control
  - Can be used by third party software vendors to quickly keep up with advances we are implementing



https://pypi.org/project/epaswmm

https://github.com/USEPA/Stormwater-Management-Model/python

SWMM Python Bindings Application Example - Water Age Tracking

$$\frac{\partial C}{\partial t} = \frac{\partial uC}{\partial x} + K$$

$Where:$

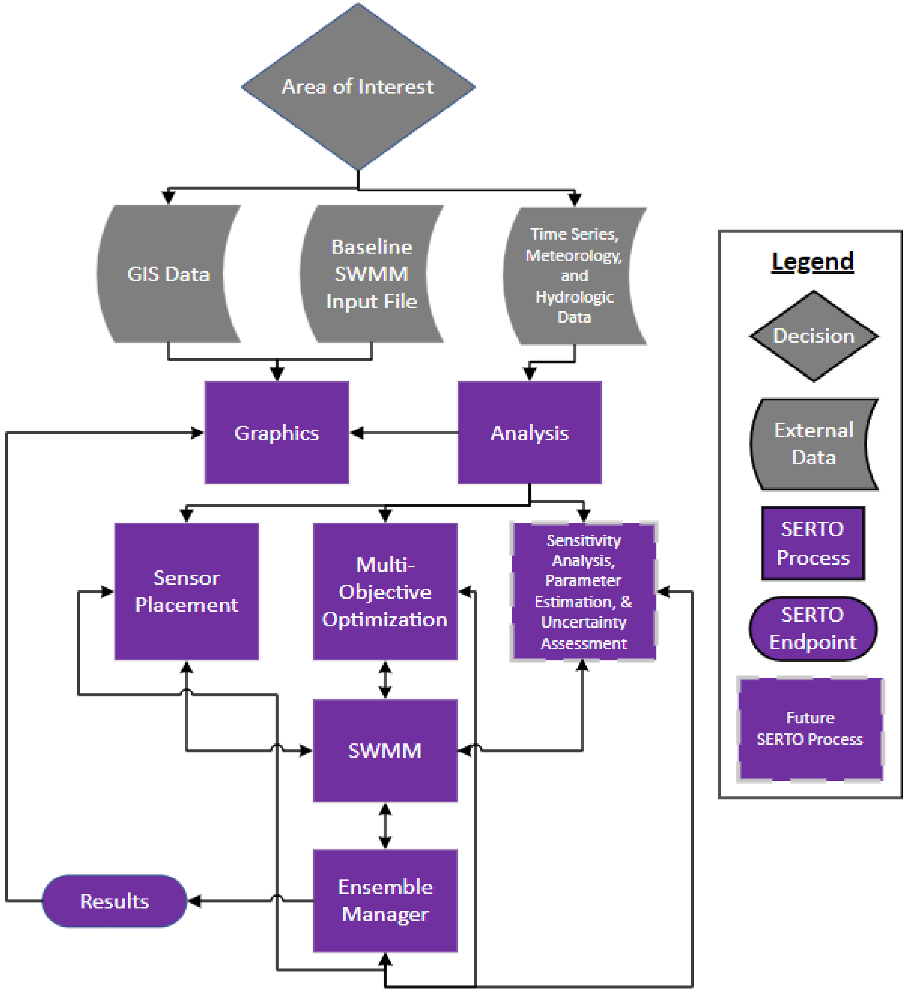
$C = Age\ of\ water$

$K = 1$

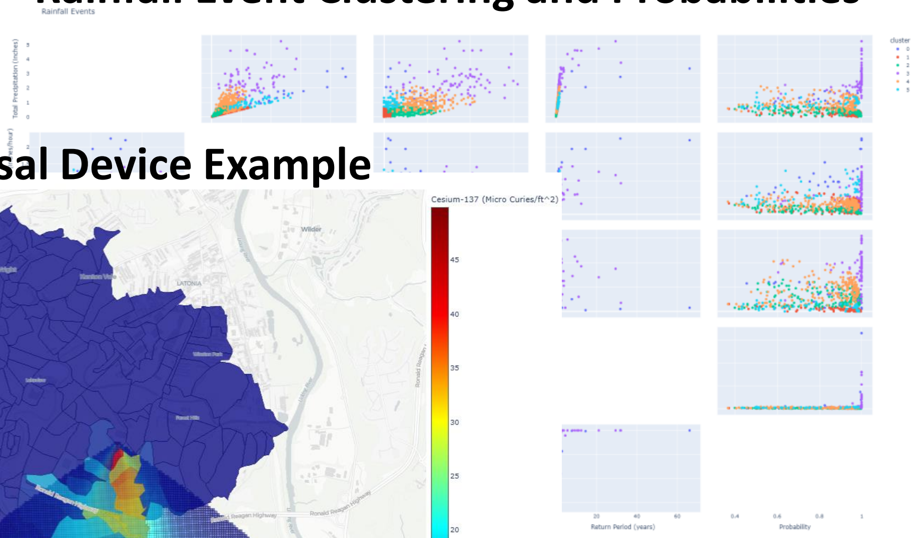
$K\ is\ injected\ as\ pollutant\ mass\ flux$
$using\ python\ API$

```python
from epaswmm import solver, output

with solver.Solver(
        inp_file=swmm_input_file,
        rpt_file=swmm_report_file,
        out_file=swmm_output_file
) as swmm_solver:

    swmm_solver.start()

    for index, (elapsed_time, current_datetime) in enumerate(swmm_solver):
        for link_name, link_index in link_indexes.items():
            volume = swmm_solver.get_value(
                object_type=solver.SWMMObjects.LINK,
                property_type=solver.SWMMLinkProperties.VOLUME,
                index=link_index
            )

            age_increase = volume

            swmm_solver.set_value(
                object_type=solver.SWMMObjects.LINK,
                property_type=solver.SWMMLinkProperties.POLLUTANT_LATERAL_MASS_FLUX,
                index=link_index,
                value=age_increase,
                sub_index=0
            )
```

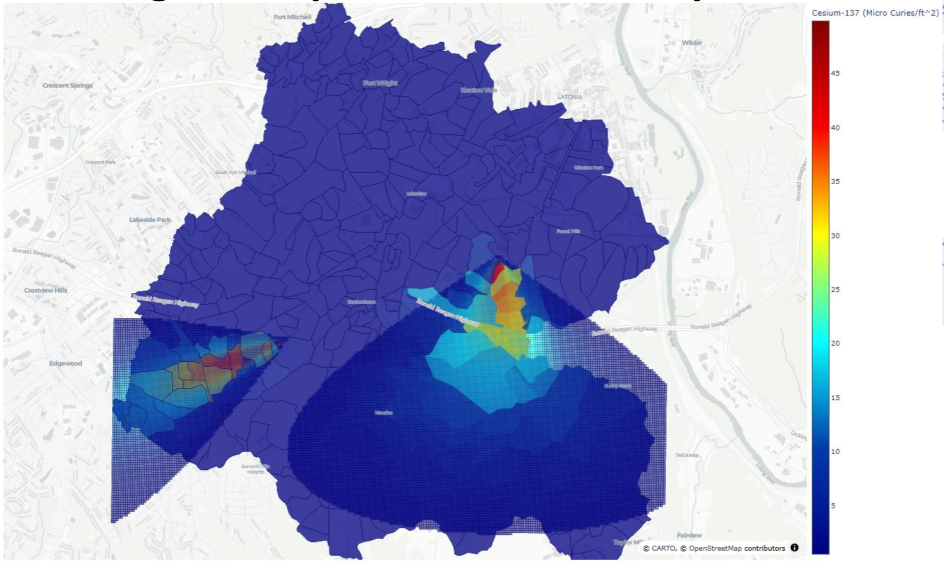
SWMM Python Tools Ecosystem - SERTO



Rainfall Event Clustering and Probabilities

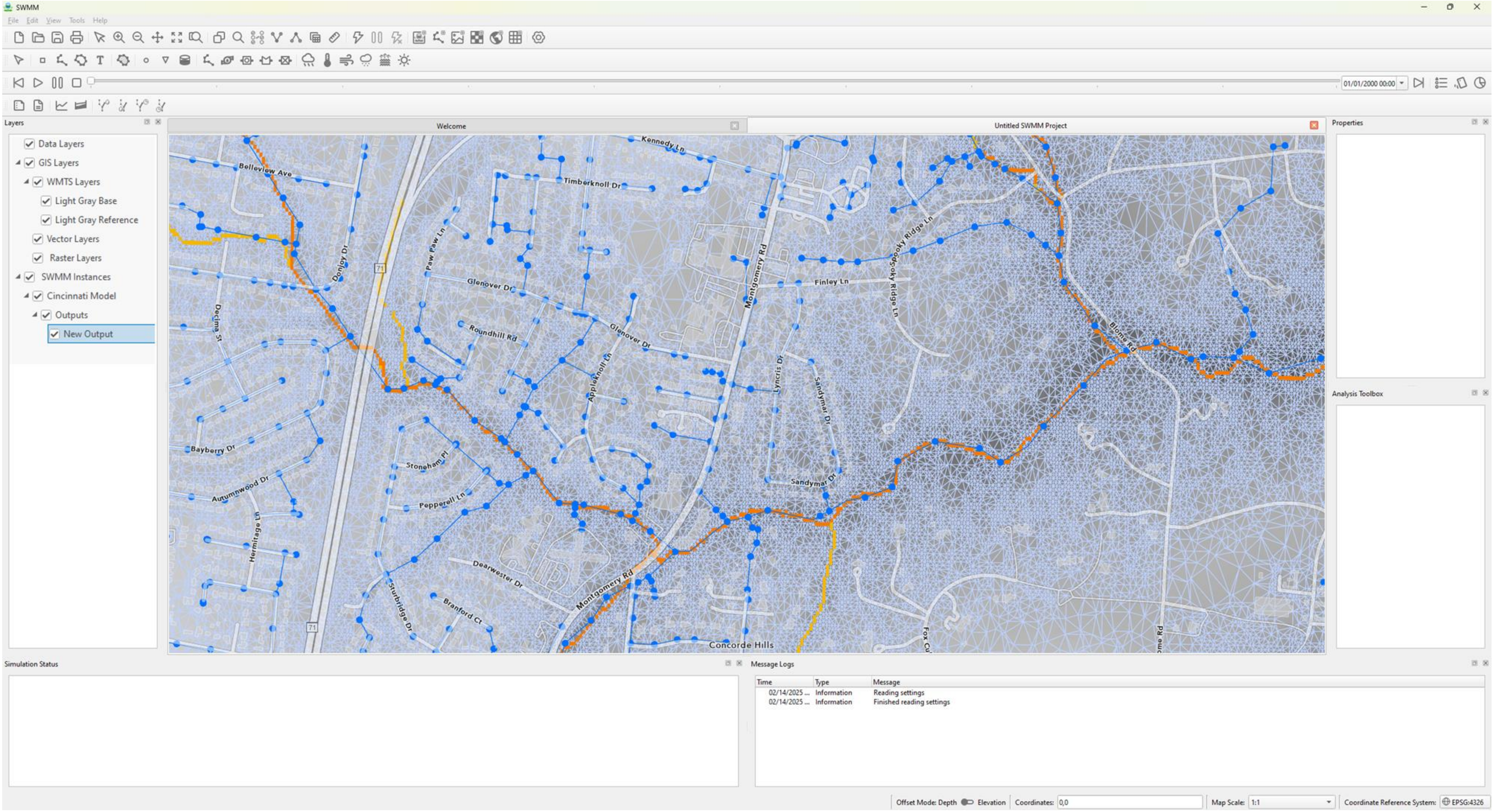


Radiological Dispersal Device Example



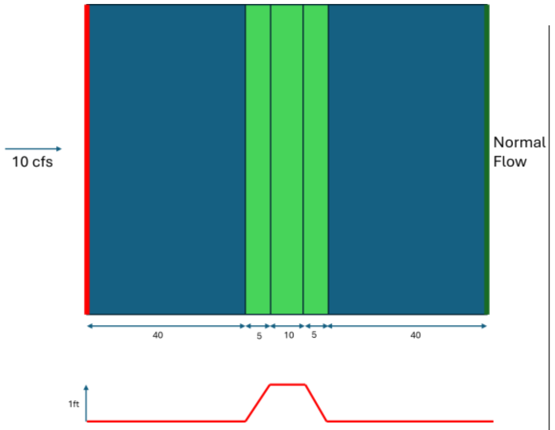
- Model calibration, uncertainty assessment, sensitivity analysis
- Green and gray infrastructure sizing and placement
- Sampling Plan Optimization
- Real Time Control Sensor Placement

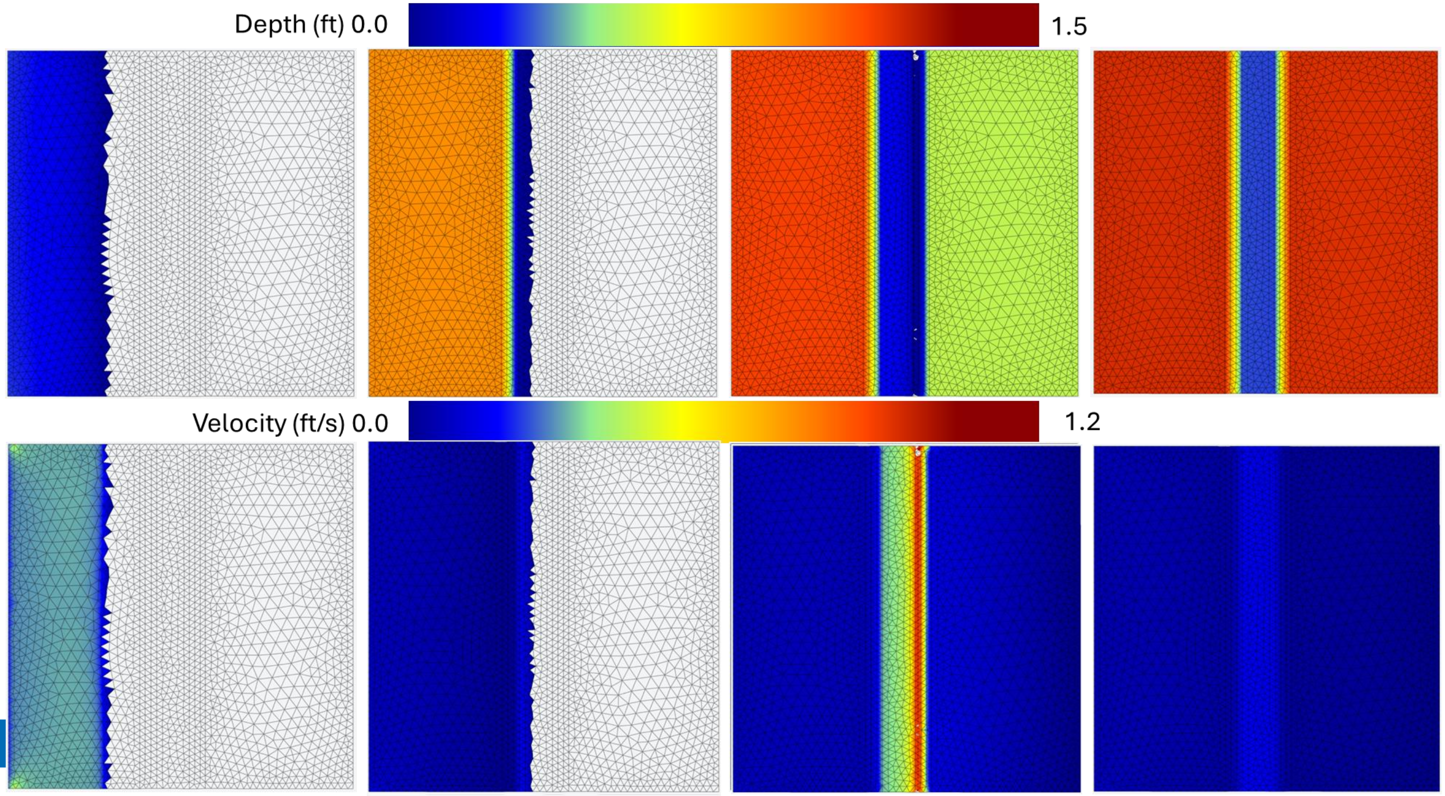
Towards Spatially Explicit Model Development with SWMM



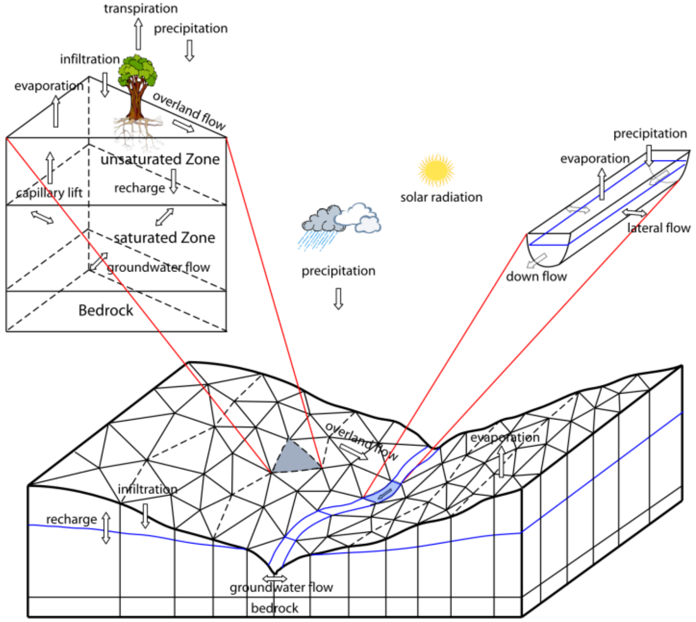
A Spatially Explicit Coupled Overland and Groundwater Flow Model

Example preliminary testing results





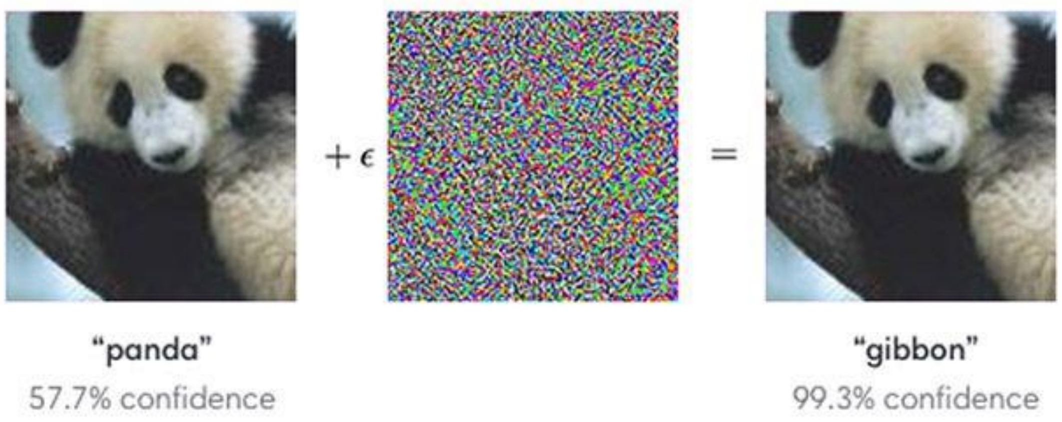
- Semi-discrete fine volume numerical approximation of overland flow and a two-zone groundwater model (i.e., unsaturated upper and lower saturated zone model)
- Solves diffusive wave approximation of shallow water equations (i.e., no local or convective acceleration)
- Compromise between kinematic wave currently implemented in SWMM and full dynamic wave implemented in models like HEC-RAS
- Accounts for backwater conditions



Qu, Y., Duffy, C.J., 2007. A semi-discrete finite volume formulation for multiprocess watershed simulation. Water Resources Research 43, 2006WR005752. https://doi.org/10.1029/2006WR005752

Role of AI in the Future of SWMM

- Generally, more accurate and less computationally expensive than traditional hydrologic models
- However, challenges remain if deep learning models are to be used to reliably predict hydrologic and hydrodynamic responses
- Challenging areas include:
  - Non interpretable weights
  - Uncertainty characterization
  - Robust models less likely to be fooled by malicious/erroneous inputs
  - Extrapolation beyond training data
  - Large training data requirements
  - Generalizability and going beyond point predictions (e.g., flow, temperature) to predicting over meshes and network in space and time



Eykholt, K., Evtimov, I., Fernandes, E., Li, B., Rahmati, A., Xiao, C., Prakash, A., Kohno, T., Song, D., 2018. Robust Physical-World Attacks on Deep Learning Models.

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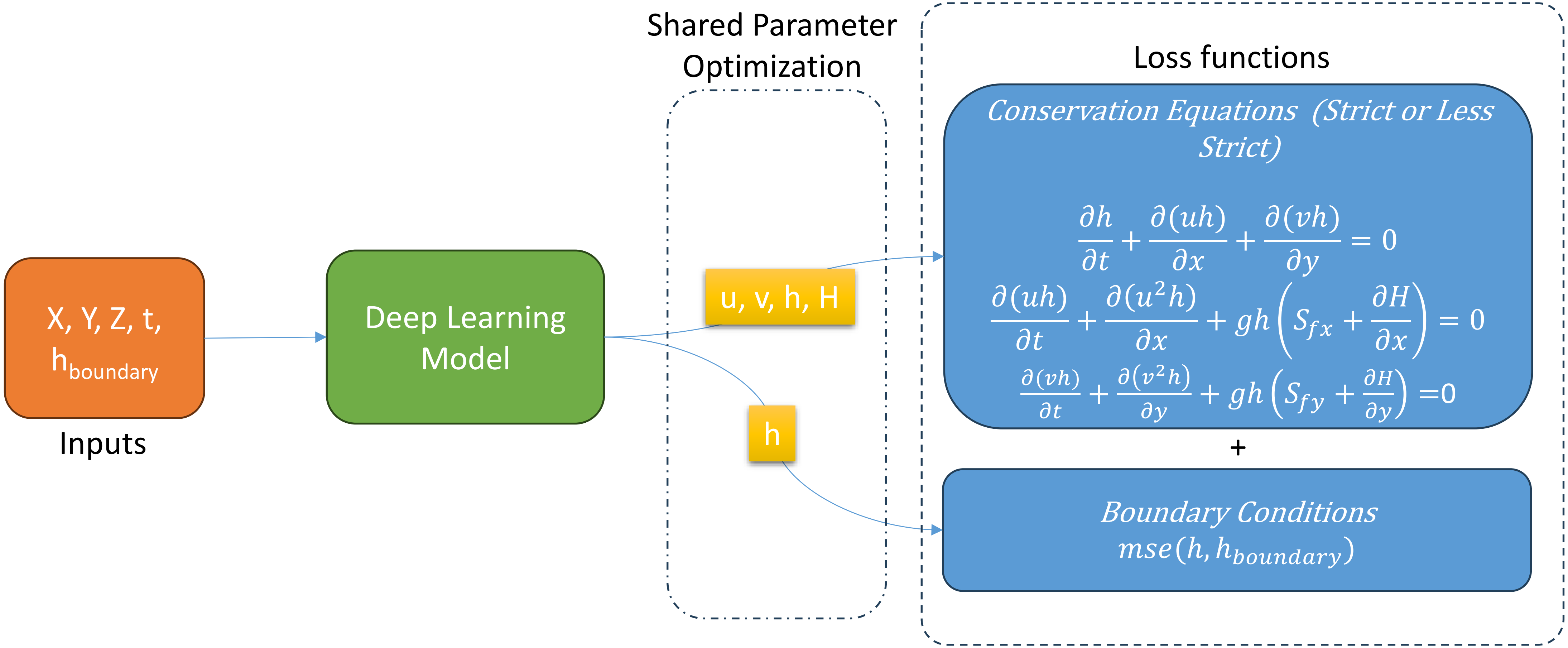
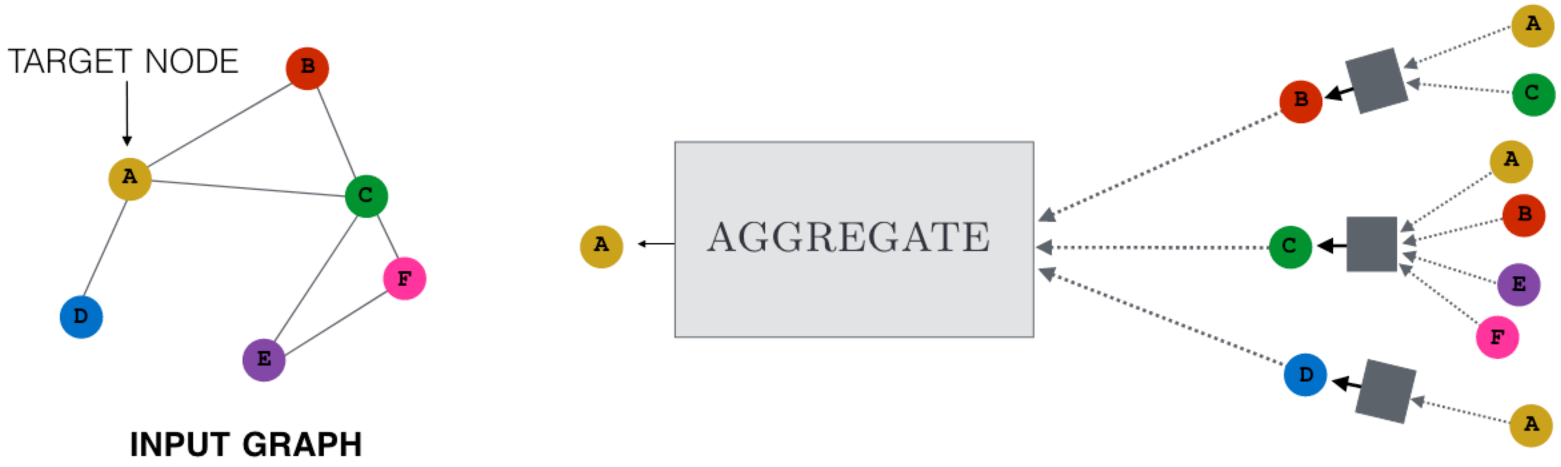
Role of AI in the Future of SWMM – Physics/Process Informed/Guided AI



Physics Informed Graph Neural Networks



$$\mathbf{h}_u^{(k)} = \sigma\left(\mathbf{W}_{\text{self}}^{(k)}\mathbf{h}_u^{(k-1)} + \mathbf{W}_{\text{neigh}}^{(k)}\sum_{v\in\mathcal{N}(u)}\mathbf{h}_v^{(k-1)} + \mathbf{b}^{(k)}\right)$$

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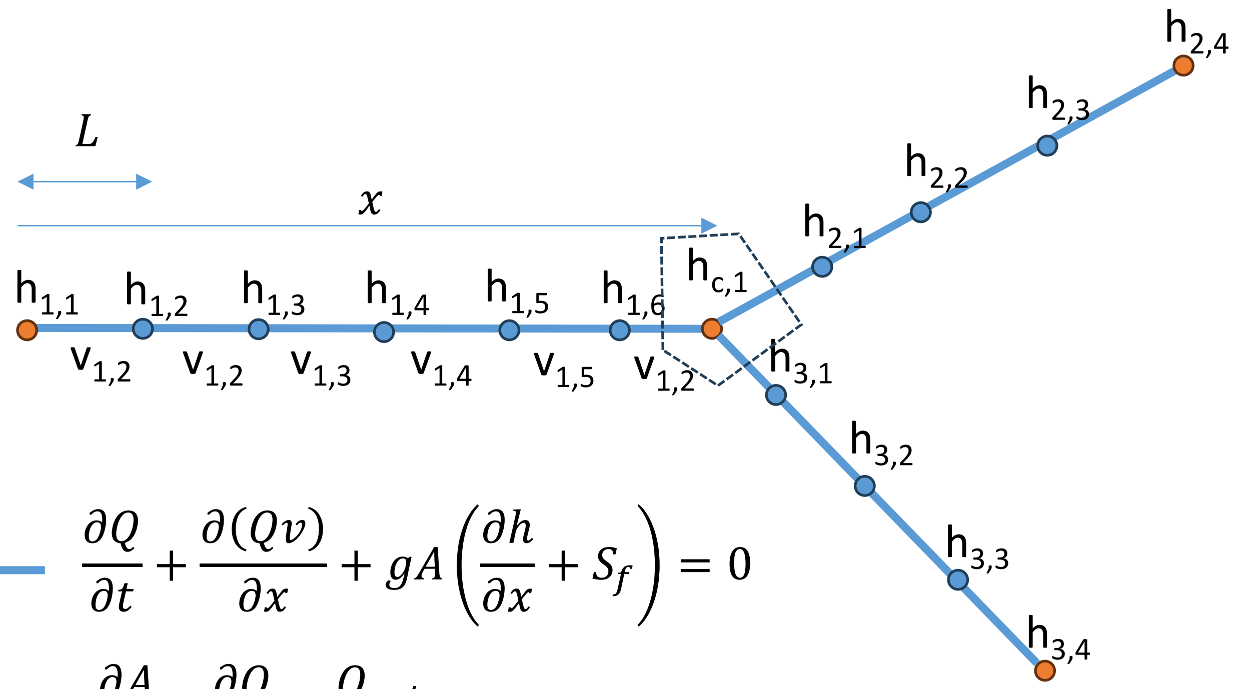
Physics Informed Graph Neural Network for Hydraulic Routing

- Staggered arrangement is used where velocity is calculated for conduits and level for nodes
- Inflow boundary conditions applied directly in continuity error loss formulation
- Level and water level slope applied as loss functions using mean square error



$$\frac{\partial Q}{\partial t} + \frac{\partial (Qv)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f\right) = 0$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = \frac{Q_{ext}}{L}$$

$$\frac{\partial h}{\partial t} = \frac{\sum_{n=1}^{N} Q_n + Q_{ext}}{\sum_{n=1}^{N} A_n^{\frac{L}{2}}}$$

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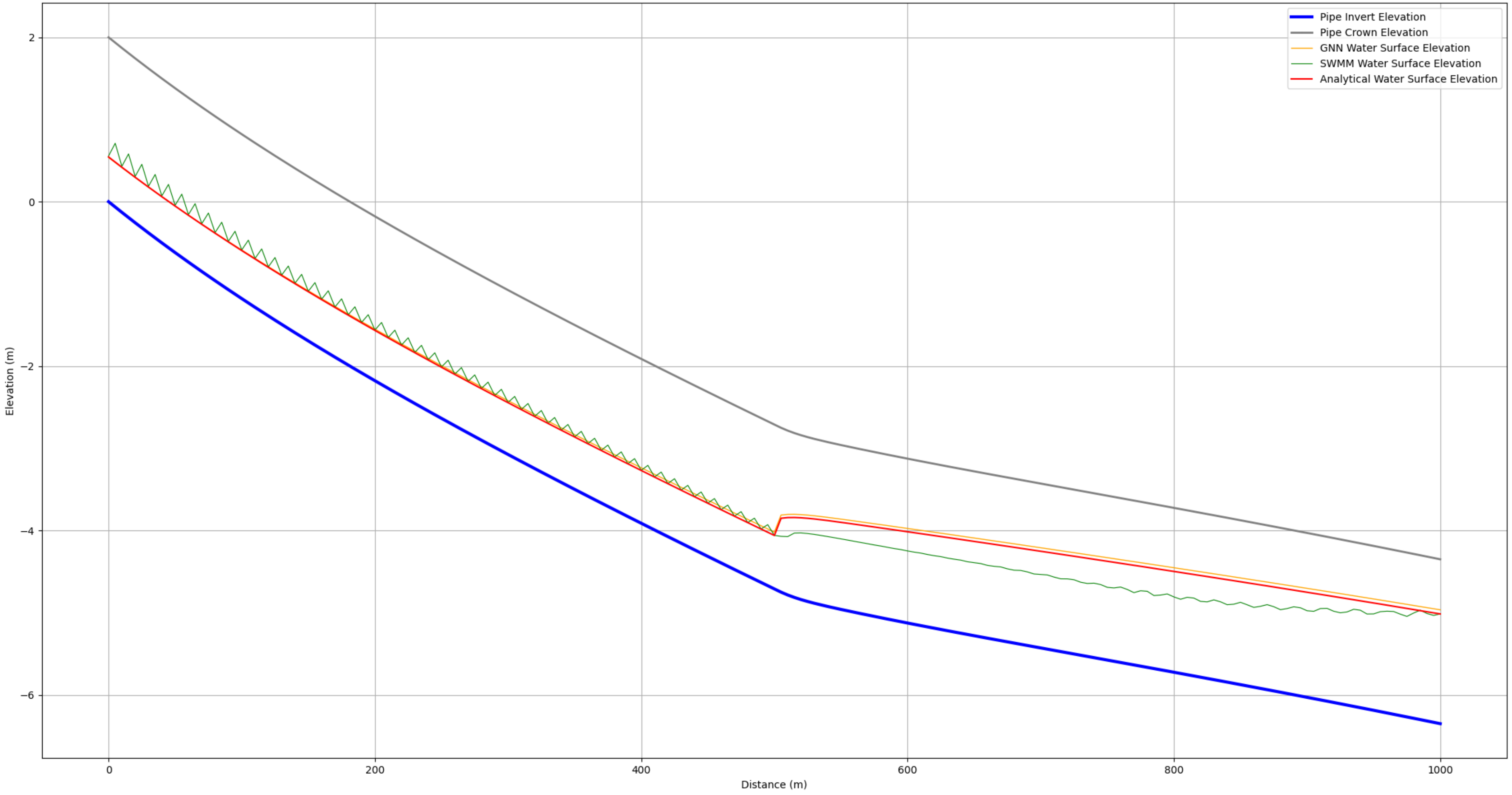
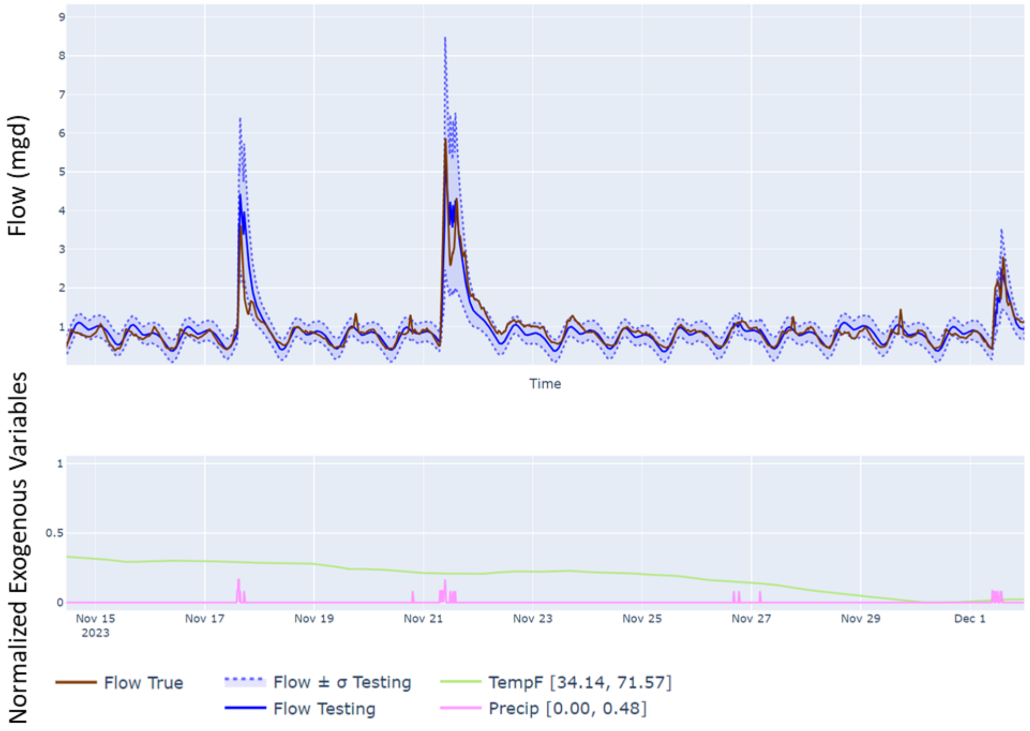
Analytical Solution vs. GNN vs. SWMM For Hydraulic Jump



Physics Constrained Deep Antecedent Moisture Model

- $\mathrm{Q} = S(t) + AMM(t, R, T)$
- Sanitary flow model $S(t)$
  - $S(t) = \sum_{n=1}^{N} \left(a_n \cos\left(\frac{2\pi nt}{P}\right) + b_n \sin\left(\frac{2\pi nt}{P}\right) \right)$
    - $a = N(\mu_a, \sigma_a)$
    - $b = N(\mu_b, \sigma_b)$
  - $a_n = Cosine\ constant$
  - $b_n = Sine\ constant$
  - $t = Time$
  - $P = Period\ of\ comoponent\ of\ sanitary\ signal$
- Semi-empirical antecedent moisture model $AMM(t, R, T)$
  - $TF_t = m \times MAT_t + b$
    - $b = N(\mu_b, \sigma_b)$
    - $m = N(\mu_m, \sigma_m)$
  - $RF_t = TF_t \times P_{t-1} + AMRF \times RF_{t-1}$
    - $AMRF = N(\mu_b, \sigma_b)$
  - $AMM_t = (AC + RF_t) \times P_t + SF \times Q_{t-1}$
    - $AC = N(\mu_{AC}, \sigma_{AC})$
    - SF= $N(\mu_{SF}, \sigma_{SF})$
  - $MAT_t = Moving\ average\ temperature$
  - $m = Slope\ paramter$
  - $b = Constant\ parameter$
  - $TF_t = Temperature\ factor$
  - $RF_t = Response\ factor$
  - $P = Precipitation$
  - $AMRF = Antecedent\ Moisture\ Retention\ Factor$
  - $P = Affine\ constant$
  - $SF = Shape\ Factor\ Constant$
  - $AC = Affine\ Constant$



OHM Advisors, Czachorski, R., 2022. Modeling Rainfall–Runoff Responses and Antecedent Moisture Effects Using Principles of System Identification. JWMM. https://doi.org/10.14796/JWMM.C482

Next Steps

- EPA ORD will continue to maintain and advance SWMM for the digital water transformation
- Expand the unit test coverage of the SWMM and regression tests to ensure continued accuracy and quality of the SWMM code
- Advancements will go through EPA's rigorous internal review process to ensure continued confidence in the use of SWMM
- Continue conversations with stakeholders throughout the development process to make sure their views and needs are addressed
- We are excited about the future of SWMM and invite practitioners, researchers, to provide feedback and suggestions on future directions

Contact

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GitHub

https://github.com/USEPA/Stormwater-Management-Model
https://github.com/USEPA/SWMM-GUI

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