Water Resour Manage (2017) 31:3177–3188
DOI 10.1007/s11269-017-1699-1

Smart Water Network Modeling for Sustainable and Resilient Infrastructure

Paul F. Boulos[1]

Received: 3 April 2017 / Accepted: 2 May 2017 /

Abstract Urbanization can significantly increase the load on aging, inefficient and already strained sewer infrastructure, resulting in catastrophic pipe failure, unwanted spillage, property damage, and serious threat to public health. Urbanization can also dramatically alter the natural water cycle, resulting in diminished water quality, increased frequency and severity of flooding, channel erosion and destruction of aquatic habitat. Recent advances in smart water network (SWN) modeling technology have played a crucial and growing role in addressing these challenges. SWN technology has equipped practicing engineers with a comprehensive set of analytical decision making tools designed to help them preserve structural integrity, manage and reduce the risks of sewer overflow and urban runoff, improve resiliency and keep their urban drainage networks operating well into the future. These advances propel routine conveyance system analysis from basic planning and design to two-dimensional surface/subsurface flow modeling, real-time operation and control, analytical risk-based asset integrity and condition assessment, and optimal selection and placement of green infrastructure based on cost and effectiveness. SWN is providing critically needed support to federal, state, and local agencies and watershed practitioners — not only in optimizing their integrated water management and adaptation strategies, but in ensuring sustainable drainage, addressing environmental quality restoration and protection needs in urban and developing areas, and improving communities' resiliency. It is also within the grasp of utilities of all sizes, but they need to seize the opportunity.

Keywords Smart water · Network modeling · Real-time · Asset management · Green infrastructure · Optimization

---

✉ Paul F. Boulos
paul.boulos@innovyze.com

[1] Innovyze, Broomfield, CO, USA

1 Introduction

The world's urban population has grown rapidly from 746 million in 1950 to 3.9 billion in 2014. It is expected to surpass six billion by 2045. Conversely, the world's rural population has grown slowly since 1950 and is expected to reach its peak around 2020. It is now close to 3.4 billion and is expected to decline to 3.1 billion by 2050. In 2014, there were 28 mega-cities with 10 million inhabitants or more worldwide. That number is projected to increase to 41 by 2030 (UNDESA 2014). Compounding the urbanization problem is the condition of the world's conveyance systems. Many have well exceeded their design lives and have received inadequate upgrade, maintenance, and repair over time, with capital spending unable to keep pace with needs. Additional load will result in increased stress, decreased efficiency, and rapid deterioration and failure of these critical infrastructures. Managing urban areas is becoming one of the most important development challenges of the 21st century. Sustainable urban drainage management is of paramount importance.

The United States, with around 800,000 miles of public sewer mains (many approaching 100 years old) and 772 cities with combined sewer systems, is no exception. Outdated sewer systems pour over 850 billion gallons of storm water mixed with raw sewage into rivers, lakes, streams and estuaries each year, causing serious water quality problems and threatening drinking water supplies. To cite one example, more than 23 billion gallons of raw sewage and other pollutants pour into New Jersey's rivers and bays each year because aging sewer systems are overwhelmed during heavy rains. The spills occur dozens of times each year, whenever there's a significant rainfall. They make people sick, threaten local drinking water and kill aquatic animals and plants. In one 1993 case in Milwaukee, more than 400,000 people got sick and over 100 died after the cryptosporidium parasite contaminated drinking water taken from Lake Michigan. A study published in the New England Journal of Medicine suggested untreated sewage in the lake could have been the culprit. To aggravate the problem, the USEPA estimates that there are at least 40,000 sanitary sewer overflows (SSOs) and thousands of combined sewer overflows (CSOs) each year. The agency also estimates that as many as 5500 people get sick every year from direct exposure to pollutants discharged from sewer overflows near beaches. The outlook nationwide remains grim. The latest ASCE 2013 Report Card for America's Infrastructure gave the nation's wastewater a near failing grade of D — a very slight improvement over the D minus given in the last Report Card, issued in 2009. Yet this critical infrastructure is projected to see the largest investment gap, falling 73% short of needs. That gap will only widen with time, and addressing it will become increasingly more expensive. This does little to assuage the public's health and economic needs or maintain its confidence in the ecological health of the nation's waterways.

As the urban population grows and sprawling urban development continues, more land is converted to impervious surfaces (e.g., driveways, sidewalks, residential rooftops, patios, public buildings, commercial structures, parking lots, and roads) that deflect rather than absorb falling rain and snowmelt and allow it to run off streets, lawns, and other sites. The resulting runoff can carry many types of pollutants (e.g., road salt, heavy metals, bacteria, hydrocarbons, organics, fertilizers, pesticides, nutrients, oil, grease, toxic chemicals, pet droppings, construction materials, particulates from pavement breakdown, and trash) into ponds, rivers, streams, drinking water aquifers and beaches. Stormwater runoff is one of the major threats to water quality in the United States and is linked to chronic and acute illnesses (Gaffield et al. 2003). The U.S. Environmental Protection Agency has documented widespread impairments in surface water quality largely attributable to stormwater runoff. These impairments constitute approximately 7641 mile^2 of estuaries, 10.45 million acres of lakes, and 246,002 miles of rivers (EPA 2004). In addition to deteriorating the quality of the receiving waterways and negatively impacting aquatic life, impervious surfaces also affect the quantity of runoff, increasing the occurrence and intensity of downstream floods as well as lowering groundwater tables and decreasing their recharge rates. Urban development also causes changes in the watershed hydrologic regime, with higher peak runoff resulting in increased stream bank erosion, clogged stream channels, suspended sediments and habitat damage.

The absence of open land to absorb extra urban runoff and remove excess nutrients and other chemical contaminants can lead to permanent damage to water quality and habitat. Compounding this problem, global climate change is expected to increase the frequency and magnitude of rain and large storms in some regions, causing more runoff, coastal flooding, and coastal erosion. It can also bring warmer water and air temperatures, spurring the growth of harmful algae and the accompanying threat to the health of humans and wildlife as well as altering the seasonal water cycle.

The traditional stormwater management approach has focused on collecting and transporting stormwater runoff through a structural conveyance network to a centralized facility (e.g., detention basin, wet pond), where it is stored, treated and discharged downstream. Today, advances in site planning and design have produced a number of effective stormwater control strategies for minimizing and even preventing adverse runoff impacts and providing necessary treatment closer to the origin of those impacts. These cost-effective, sustainable, and environmentally friendly strategies are known collectively as Best Management Practices/Low Impact Developments (BMPs/LIDs). BMPs include wet/dry ponds, rain gardens, porous pavement, infiltration trenches, grass swales, and filter strips (Fig. 1). LID is an approach to land development (or re-development) that works with nature to manage stormwater as closely as possible to its original source as rainfall. It seeks to retain a site's natural or pre-developed hydrologic response to precipitation by combining impervious area controls with small-scale BMPs. Instead of simply removing stormwater from a site without treatment, and potentially creating water quantity and quality problems downstream, water is stored, reused, and treated closer to its source. By implementing LID-BMP principles and practices, water can be managed in a way that reduces the impact of built areas and promotes the natural movement of water within an ecosystem or watershed. This approach complements, and sometimes replaces, traditional stormwater management systems, and transforms runoff into a resource to be preserved and protected, not a nuisance to be eliminated. For example, roof runoff can be captured and stored in rain barrels for plant watering and other uses. Runoff can also be directed to rain gardens for treatment and landscape enhancements. Applied on a broad scale, LID-BMP strategies can maintain or restore a watershed's hydrologic and ecological functions. LID has been characterized as a sustainable stormwater practice by the Water Environment Research Foundation and others. Also known as Green Infrastructure (GI), LID can help communities protect the environment and human health while providing other social and economic benefits, allowing communities to achieve more for their money (EPA 2014). It can be applied to new development, redevelopment, or as retrofits to existing development, and has been adapted to a range of land uses, from high density ultra-urban settings to low density development.

Recent advances in smart water network (SWN) modeling technology are playing a crucial and growing role in addressing these urbanization challenges. SWN technology is equipping practicing engineers with a comprehensive set of analytical decision making tools designed to help them preserve structural integrity, manage and reduce the risks of sewer overflow and

(a) *Constructed wetland* (b) *Infiltration basin*

(c) *Bio-retention* (d) *Surface sand filter*

(e) *Non surface sand filter* (f) *Rain barrel*

Fig. 1 Commonly used types of BMP-LID

(g) *Cistern* (h) *Wet pond*

(i) *Dry pond* (j) *Grassed swale*

(k) *Infiltration trench* (l) *Vegetated filter strip*

(m) *Green roof* (n) *Porous pavement*

Fig. 1 (continued)

urban runoff, improve resiliency and keep their urban drainage networks operating well into the future. They are normally integrated with geographic information systems (GIS) to support development of conveyance networks, 2D surface mesh generation and spatial placement, and site suitability of green infrastructure options, and also provide geo-processing functions and visualization facilities for display and manipulation of data and results. These advances propel routine conveyance system analysis from basic planning and design to two-dimensional surface/subsurface flow modeling, real-time operation and control, analytical risk-based asset integrity and condition assessment, and optimal selection and placement of green infrastructure based on cost and effectiveness. SWN is providing critically needed support to federal, state, local and watershed practitioners — not only for optimizing their integrated water management and adaptation strategies, but also for ensuring sustainable drainage, addressing environmental quality restoration and protection needs in urban and developing areas, and improving communities' resiliency.

SWN models can be divided into five general categories. They can be used independently or in any combination.

2 SMART Water Network Modeling

2.1 Dynamic Rainfall-Runoff Simulation Models

These models represent the most effective and viable means for simulating runoff quantity and quality conditions from single storm event or long-term (continuous) storm conditions in primarily urban areas (Fig. 2). The runoff model operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing (dynamic wave) model transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators, and can model such phenomena as backwater effects, flow reversals, pressurized flow, and entrance/exit energy losses. This model solves the one-dimensional St. Venant equations that govern the unsteady flow of water through a drainage network of channels and pipes along with using the continuity principle at the junctions. Together, the models track the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during the simulation

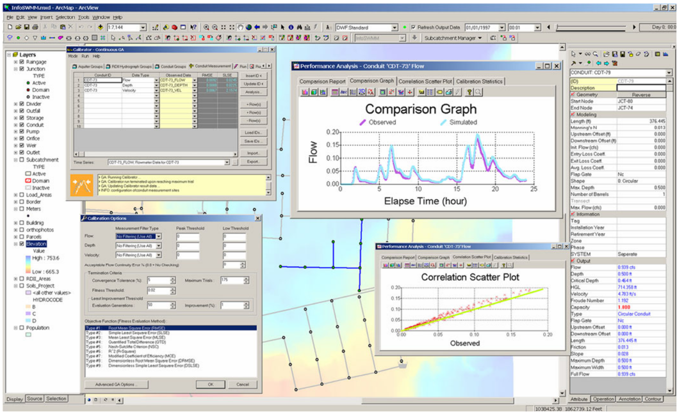


Fig. 2 Dynamic rainfall-runoff simulation model

period. Through their predictive capabilities, they can estimate the production of pollutant loads associated with stormwater runoff including dry-weather pollutant buildup over different land uses, pollutant wash-off from specific land uses during storm events, direct contribution of rainfall deposition, reduction in dry-weather buildup due to street cleaning, reduction in wash-off load due to treatment in BMPs, entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system, routing of water quality constituents through the drainage system, and reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels. They can also model the hydrologic performance of specific types of small LID controls including permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, rooftop disconnection and vegetative swales. Such capabilities allow engineers and planners to accurately represent any combination of LID controls within a study area to determine their effectiveness in managing stormwater and combined sewer overflows (Nicklow et al. 2006; Rossman 2010).

2.2 Integrated 1D-2D Models

These models essentially consist of dynamic couplings of one-dimensional (1D) hydrodynamic simulation of flows in rivers, open channels and pipe networks with two dimensional (2D) hydrodynamic simulation of surface (overland) flooding in the urban environment and river floodplain (Fig. 3). Sources of 2D surface flows can be overbank flooding from rivers and streams, flooding from minor systems, and distributed rainfall. The surface area is represented by a detailed 2D mesh that fits around complex urban geometries. The spatial and temporal distribution of water depths and flows are determined by numerically solving the Shallow Water equations. Both structured and non-structured meshes using triangles and quadrangles make up the surface grid. By allowing the simultaneous solution of the processes of rainfall and runoff, urban drainage, river flow and flooding, the integrated 1D-2D models are able to efficiently predict flood risks and support cost-effective drainage design and management. They can also be effectively used to estimate the potential flood risks of any drainage system and develop reliable and cost-effective design, management and operational strategies (Boulos and Walker 2015).

2.3 Real-Time Simulation Models

These models extend the utility of dynamic rainfall-runoff simulation and 1D-2D models to real-time operational applications (Fig. 4). This is accomplished by synthesizing SCADA, radar rainfall and other real time telemetry data with the network models. The resulting real-time network models provide utility operators continuous real-time insights on their collection network performance. A constant stream of data (e.g. at 5, 10 or 15 min intervals) coupled with predictive modeling capabilities enables engineering operators to quickly assess events as they occur, identify potential problems before they reach a critical level, respond decisively to operational challenges, reduce overflow volumes, and minimize downstream effects. For example, operators can analyze the impact of a predicted incoming storm event and identify all areas potentially impacted by flooding or overflows. Alternative mitigating solutions can then be rapidly and accurately analyzed and compared to determine the level of effectiveness and associated cost, and the most appropriate solution can be selected and quickly acted upon.

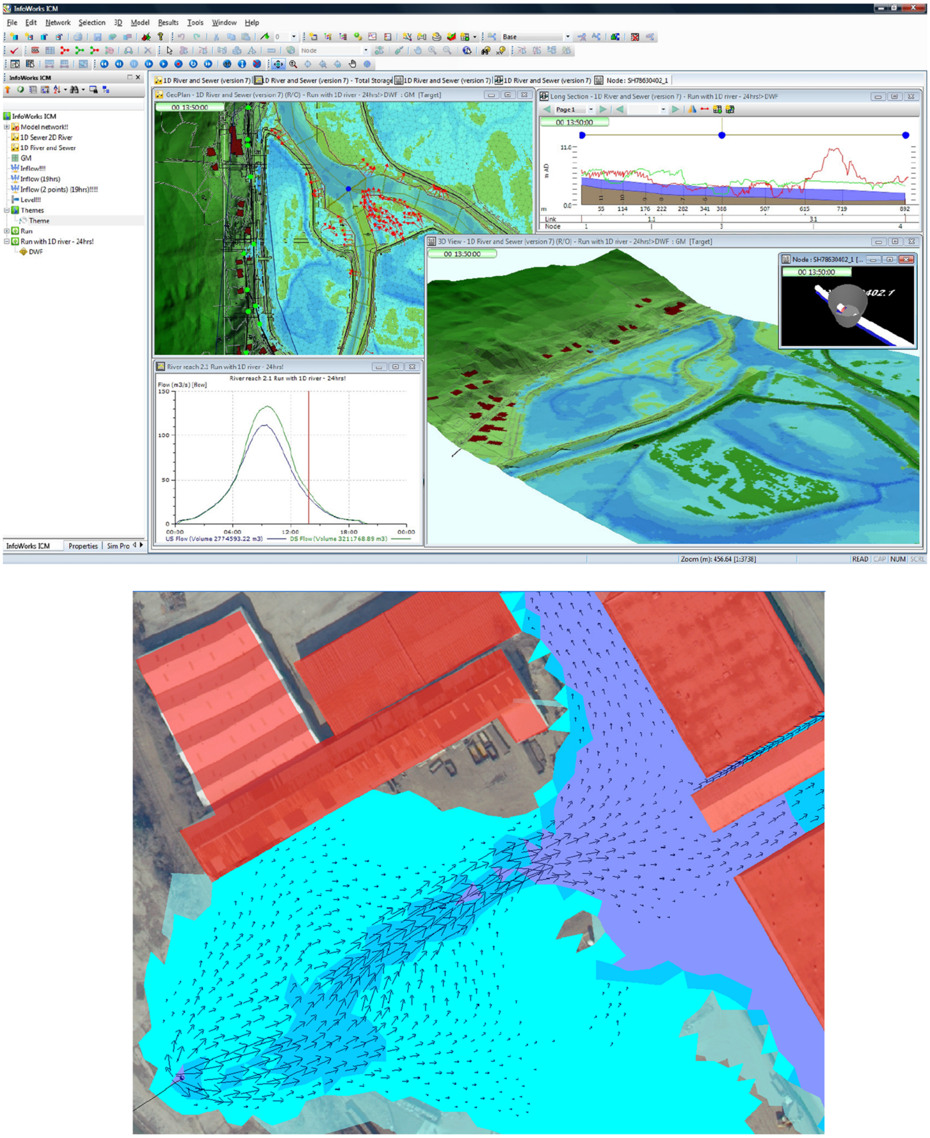


Fig. 3 Integrated 1D-2D model

Operators can also assess the effects of equipment failures, shutdowns, scheduled maintenance or repairs, and any other planned/unplanned incidents, then respond in a timely manner with appropriate countermeasures. They can also predict key network parameters (flow, depth, storage capacity, etc.) where data loggers are unavailable and predict system performance should SCADA feeds go offline. Using real-time network modeling, wastewater utilities can progress from purely reactive to more proactive network management. This can ultimately result in significantly more efficient and economical network operations, greater network integrity, and improved network maintenance and customer service.

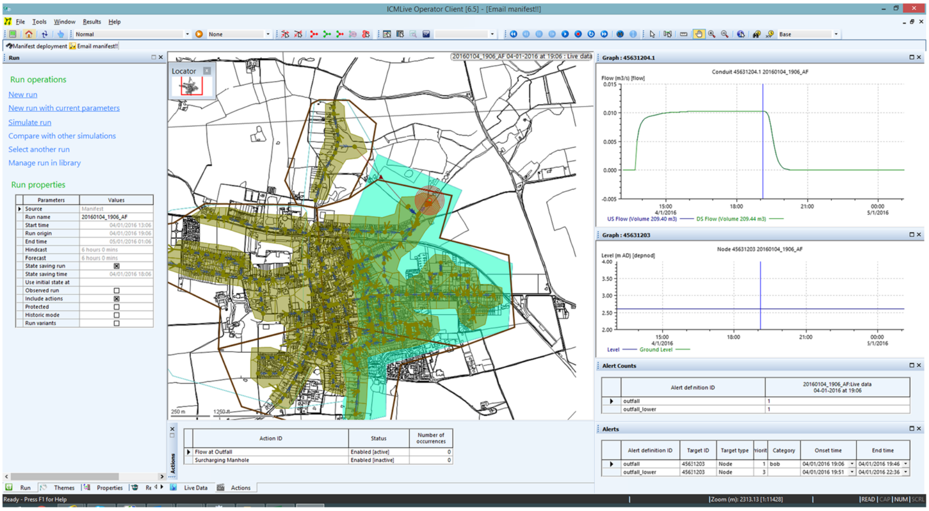


Fig. 4 Real-time simulation model

2.4 Asset Integrity Management and Capital Planning Models

These models include predictive analytics that process sewer inspection and modeling data, identify pipes requiring frequent cleaning as well as those at greatest risk of hydraulic deficiencies and/or structural failure, generate a prioritized list of all pipes requiring rehabilitation, and propose appropriate rehabilitation methods or replacement (Fig. 5). They make use of sophisticated deterioration models as the core computational basis for predicting and prioritizing future maintenance including the non-homogeneous Markov Chain (NHMC), non-homogeneous Poisson process (NHPP), Linear Extended Yule Process (LEYP), Cox proportional hazards model, and advanced

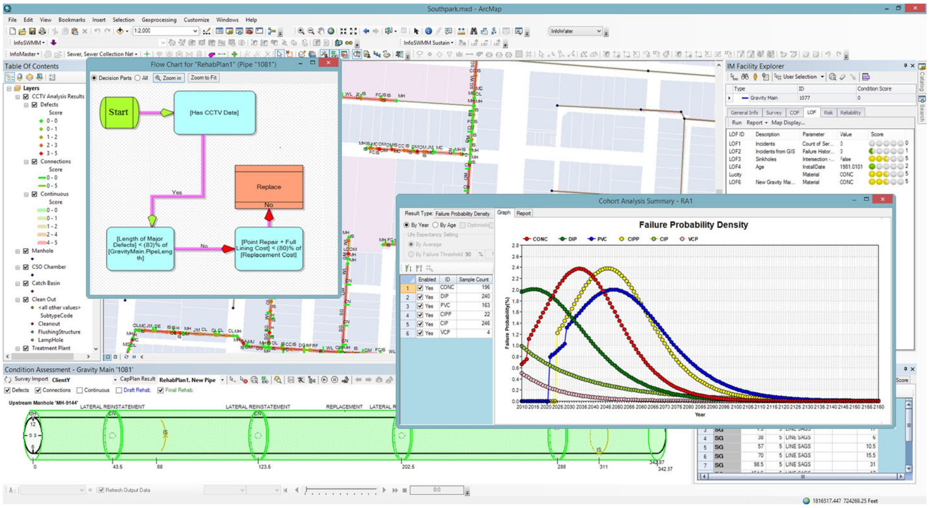


Fig. 5 Asset integrity management and capital planning model

time-based probabilistic Weibull and Herz models. They can be used to assess system structural (and O&M) condition using CCTV data, score the risk profile for each pipe in the network (taking into account both the probability and consequence of failure) and identify the worst-performing ones. The most attention can then be given to pipes at highest risk (worst performing) with the highest negative impact. For example, a sewer overflow in a sensitive, densely populated area with significant public health risks will rank higher on the priority list than an overflow in a sparsely populated area with minimal impact, even if the latter exhibits a larger overflow. Using this ranking process, wastewater utilities can track distressed areas and develop fully prioritized short- and long-term pipe replacement, rehabilitation, maintenance and management plans (phasing of network improvements) that will improve sewer system performance and work within their existing capital improvement budgets.

These models can also consider life-cycle cost analysis (LCCA). LCCA balances capital (replacement) expenditure against marginal cost to minimize the overall cost of asset ownership (Fig. 6). Marginal cost can be expressed as the present value of the expected risk cost (or consequences) of pipe failure, the accelerating cost to maintain it (maintenance cost) and declining level of service (operational cost). These costs can also include internal resources and overheads; leakage, additional pumping, and traffic and disruption costs; and costs related to sustainability, resiliency, greenhouse gas emissions, and health and safety. At the same time, the discounted (or present value) replacement cost declines as pipe renewal is deferred. The total ownership cost, or expected life-cycle cost, typically forms a convex shape, where the minimum point (i.e., when the gradient is zero) depicts the optimal time of replacement. This optimal replacement time represents the end of the pipe's economic life. Knowing the full economic costs and revenues generated by sewer systems will enable utilities to determine a financial forecast and long-term funding strategy and allocate utility resources in the most efficient way.

2.5 Urban Stormwater Treatment and Analysis Models

These models are used to determine optimal selection and placement of BMPs and LIDs at strategic locations in urban watersheds, addressing the dual objectives of pollution and flood

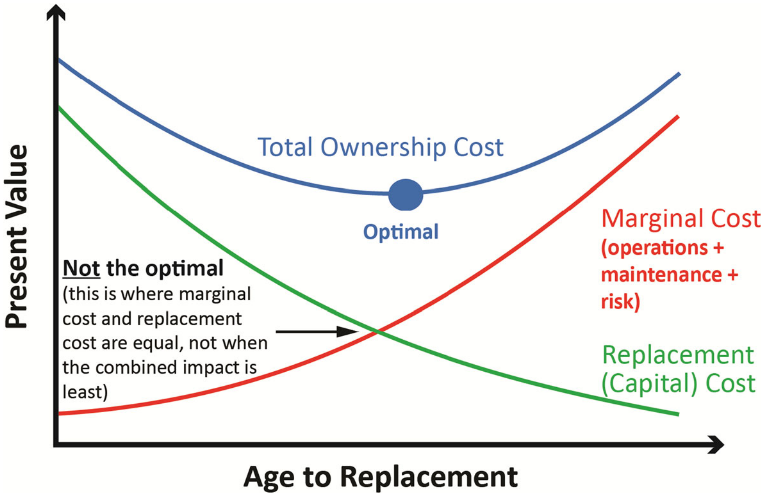
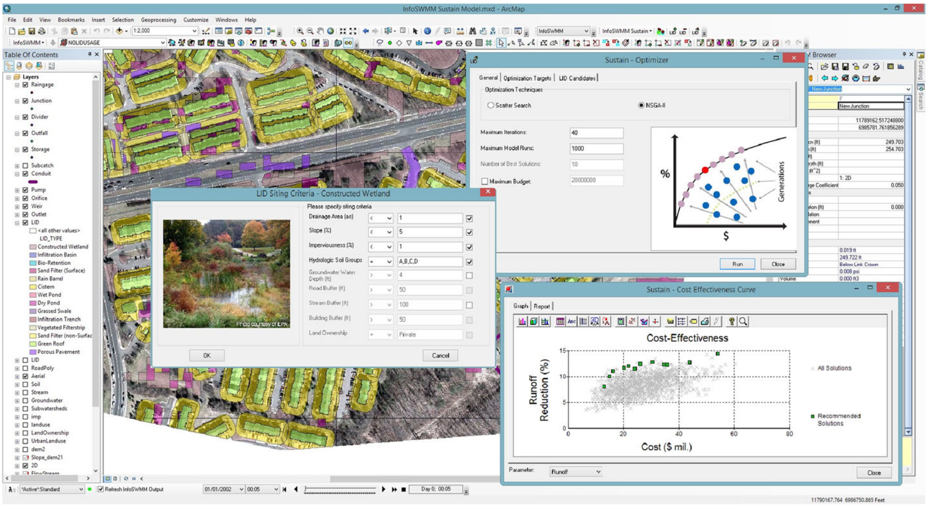


Fig. 6 Optimal LCCA timing of pipe replacement



LID Siting Criteria - Constructed Wetland

Please specify siting criteria

Drainage Area (ac)	<	1	☑
Slope (%)	<	5	☑
Imperviousness (%)	<	1	☑
Hydrologic Soil Groups	=	A,B,C,D	☑
Groundwater Water Depth (ft)	>	4	☐
Road Buffer (ft)	>	50	☐
Stream Buffer (ft)	>	100	☐
Building Buffer (ft)	>	50	☐
Land Ownership	=	Private	☐

Sustain - Optimizer

Optimization Techniques: ○ Scatter Search ● NSGA-II

Maximum Iterations: 40

Maximum Model Runs: 1000

Number of Best Solutions: 10

☐ Maximum Budget: 20000000

Sustain - Cost Effectiveness Curve

Parameter: Runoff

Fig. 7 Urban stormwater treatment and analysis model

control (Fig. 7). The optimization module (e.g., scatter search and non-dominated sorting genetic algorithm-II) performs cost estimating and systematically compares cost and performance of LID-BMP options and their placement criteria for meeting desired flow and/or water quality targets. Figure 1a-n show the most commonly used types of BMP-LID. The decision variables consist of BMP-LID unit numbers and dimensions, a constraints set comprised of runoff volumes and pollutant load reductions, and an objective function that minimizes total costs. The output consists of cost-effectiveness curves that relate flow and/or pollutant load reductions with costs for a series of optimal solutions. These powerful features greatly assist users in developing cost-effective and reliable flow and pollution control implementation plans that are aimed at protecting source waters and meeting water quality goals (EPA 2009, 2011). They will ensure that installation and operational costs are minimized while pollutant load removal and flood mitigation are maximized. By employing increasingly sophisticated and accurate models, designers will be able to use green infrastructure in ways that maximize their effectiveness in improving the quality of urban runoff. This will reduce pollutant transportation, decrease the intensity of flooding, and increase groundwater recharge rates.

3 Conclusions

Better understanding and control of sustainable drainage management grows ever more important as the infrastructure spending gap and the world's population and urbanization increase. This unprecedented urbanization challenge has begun to strain many conveyance systems designed and operated using traditional management methods. Smart water network models will play a growing role in meeting this challenge due to their inherent ability to continuously monitor the integrity of urban drainage systems, provide warning of potential breaches in sufficient time to effectively respond, and minimize public exposure and economic impact on individuals and businesses; optimize operational efficiency and performance; enhance resiliency as well as emergency response and consequence management plans; prioritize future maintenance, rehabilitation or replacement activities; select the best placement and type of green infrastructure; assist in making informed climate change adaptation decisions; and help ensure a sustainable future for large urban areas. They also offer a number of secondary benefits for communities including groundwater recharge, improved water quality, the support of natural biodiversity, better air quality, and increased green space and recreational opportunities. These mission-critical tools integrate dynamic network simulation and optimization models with GIS and SCADA to help optimize planning and design of sustainable urban drainage systems and their operations in real time. The end result is managing complexity through simplicity.

References

Boulos PF, Walker AT (2015) Fixing the future of wastewater systems with smart network modeling. J Am Water Works Assoc 107(4):72–80

EPA (2004) National water quality inventory: report to congress http://water.epa.gov/lawsregs/guidance/cwa/305b/upload/2009_01_22_305b_2004report_factsheet2004305b.pdf

EPA (2014) Enhancing sustainable communities with green infrastructure: a guide to help communities better manage stormwater while achieving other environmental, public health, social, and economic benefits http://www2.epa.gov/sites/production/files/2014-10/documents/green-infrastructure.pdf. Accessed 18 June 2015

Gaffield SJ, Goo RL, Richards LA, Jackson RJ (2003) Public health effects of inadequately managed stormwater runoff. Am J Public Health 93(9):1527–1533

Rossman LA (2010) Storm water management model user's manual version 5.0. US. Environmental Protection Agency, Washington, DC, EPA/600/R-05/040

EPA (2009) SUSTAIN – A framework for placement of best management practices in urban watersheds to protect water quality. (Publication No. EPA/600/R-09/095

EPA (2011) Enhanced framework (SUSTAIN) and field applications for placement of BMPs in urban watersheds. (Publication No. EPA/600/R-11/144, November 2011)

Nicklow JW, Boulos PF, Muleta MK (2006) Comprehensive urban hydrologic modeling handbook for engineers and planners. Innovyze/MWH Soft Press Publisher, Broomfield, 376 pp

United Nations, Department of Economic and Social Affairs, Population Division (2014) World's urbanization prospects: The 2014 Revision, Highlights. (Publication No. ST/ESA/SER.A/352)