OPTIMIZATION OF DECENTRALIZED BMP CONTROLS IN URBAN AREAS

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ABSTRACT

This paper presents the results of a research project on urban wet-weather flow controls funded by US EPA. The project focused on techniques that are suitable for evaluating and optimizing decentralized urban BMP controls. Presented here are general approaches for conducting detailed spatial analysis, long-term precipitation data analysis, an explicit runoff routing model, and a prototype optimization model for functional land development strategies. The entire optimization decision support system (ODSS) is developed as a series of spreadsheet (SS) files.

KEYWORDS

Urban Stormwater Management, BMP Optimization, Wet-weather Flow Controls, Urban Hydrology

INTRODUCTION

The purpose of this paper is to present the results of a research project funded by US EPA. The focus of this research effort is on techniques suitable for evaluating decentralized BMP controls. A major problem domain shift in recent years is from total reliance on large, centralized control systems to better integration of decentralized controls into the overall wet-weather management system. The entire optimization decision support system (ODSS) is developed as a series of spreadsheet (SS) files. It is now possible to directly link process simulators and optimizers within a SS platform. This paper includes a project overview, spreadsheet simulation options and hierarchical approach, spatial analysis, precipitation data analysis, runoff flow routing, and optimization of functional land development strategies.

PROJECT OVERVIEW

The primary objectives of the project are to develop:

1. a model to evaluate urban sewer systems to optimize their performance in terms of cost-effectiveness during wet weather periods; and
2. modeling formulations for BMP/LID alternatives that can be incorporated into the optimization model.

To achieve the above objectives, this project performed a hierarchical approach to evaluate and/or optimize urban wet-weather flow controls (WWC). This approach consists of SS simulation and optimization options, aggregated/disaggregated spatial analysis to represent functional urban surface components, long-term precipitation data analysis, dry weather flow inputs, pollutant generation, catchment and channel flow routing, cost analysis, storm sewer optimization, and functional land development optimization with a design storm approach and a continuous simulation.

SS SIMULATION OPTIONS AND HIERARCHICAL APPROACH

The traditional formulation for a constrained optimization problem is as follows:

$$
\begin{array}{ll}
\text{Max. or min.} & Z = f(x) \\
\text{Subject to} & g(x) \leq, =, or \geq b \\
 & x \geq 0
\end{array}
\qquad (1)
$$

The constraint set, $g(x) \leq = \geq b$, includes the process characterization relationships and performance criteria. If classical mathematical programming techniques are used, then the objective function and the constraint set must be well-behaved in the mathematical sense, meaning that the relationships are linear, nonlinear but convex, etc. If the problem can be formulated as a coupled system, then the optimization methods work quite well and the optimal solution can be found quickly. However, if the objective function and/or the constraint set violate the conditions for solving a classical optimization problem, then the more flexible evolutionary solvers need to be used. Some expertise is needed to properly match the simulator and the optimizer. For example, using logical statements in the simulator may disallow the use of classical optimization methods.

A hierarchy of spreadsheet-based process simulators has been developed as part of this project, as shown in Table 1. Users can select from this menu and combine the components as they see fit to do a simulation.

SPATIAL ANALYSIS

Prior to the availability of GIS and associated databases, spatial analysis typically consisted of aggregations of land uses into major categories such as residential, commercial, and industrial. Also, the study area was divided into relatively few catchments to make the computations easier. This approach was easier to justify when the analysis focused on large, downstream controls. However, now much of the interest is in decentralized controls such as low impact development where the emphasis is the use of a larger number of smaller wet-weather flow controls instead of a smaller number of centralized controls. With very friendly GIS and database systems becoming a reality, a prototype GIS database and query system was developed for Happy Hectares to illustrate how these tools can materially improve our ability to optimize wet-weather flow controls. Lee and Heaney (2003) show how to do such analyses and that better spatial resolution can lead to much improved estimates of peak runoff rates. Major advances in our ability to evaluate urban wet-weather flow systems have come about because of having high quality GIS and associated database information that allows us to evaluate and optimize at various levels of aggregation that are infeasible without such tools. A major effort of this project has been to compile a high quality GIS and associated database for Happy Hectares.

Table 1 - Options in Urban Wet-weather Flow Simulator

Land Use	Weighted average of land uses
	GIS-based approaches
Rainfall Input	Single intensity-duration-frequency (IDF) design storm
	Storm event time series
	Measured time series
Dry Weather Flow Input	Sewage
	Infiltration/inflow (I/I)
	Irrigation onto pervious area
Depression storage and infiltration	Excess rainfall w/ Φ-index infiltration
	Excess rainfall w/ Hortonian infiltration
Evapotranspiration	Monthly data
	Daily data
	Hourly data
Pollutant generation	Annual load
	Event mean concentration (EMC)
	Measured or assumed pollutographs
Catchment runoff routing	Rational method (Single event, Peak only)
	Storage-release continuous simulation
	Time-area method
Channel flow routing	Indirect using Rational Method
	Explicit Muskingum-Cunge method
Storage/treatment	Flow routing
	Pollutant routing

Description of Happy Hectares

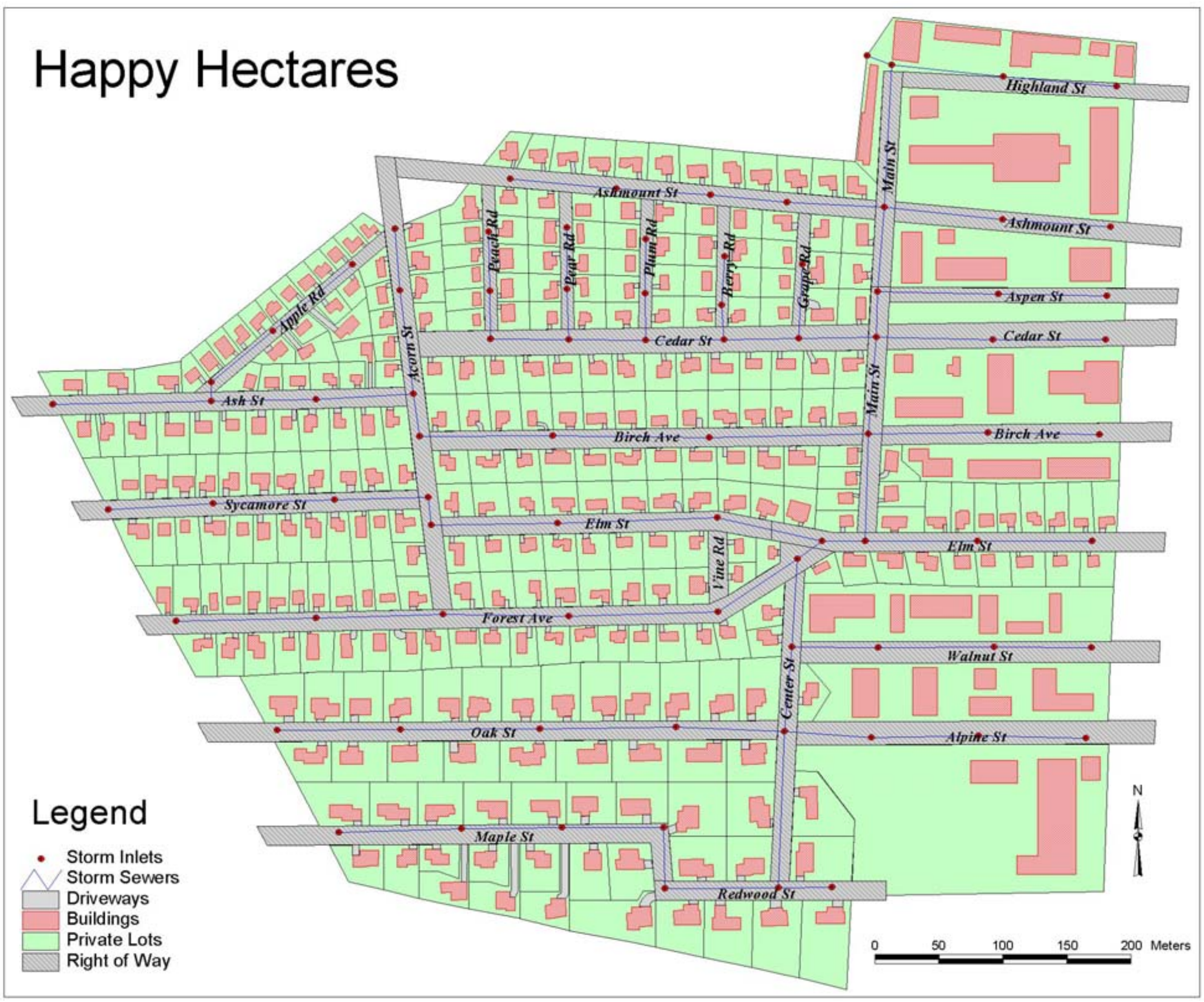
A textbook study area, nicknamed "Happy Hectares", was adapted from Tchobanoglous (1981). It is a hypothetical 44.2-hectare study area that is comprised of low to medium density residential land use, apartments, shopping centers, and a school. GIS coverage for this case study had been developed in the previous study (Heaney et al. 1999; Sample et al. 2001) but was updated in this project to facilitate performing additional analyses more realistically.

The study area was first digitized in AutoCAD, then edited for geometric consistency, i.e., parallel lines were kept parallel, polygons were joined from separated lines to make the transition to GIS easier. The existing database is updated parcel by parcel: a building and driveway are newly created for each lot, the public right of way (ROW) is divided by sub-drainage areas based on storm sewer inlets, and x and y coordinates of most spatial features are added as attribute data. The mix of land uses for the study area is summarized in Table 2. The reconstructed GIS coverage of the area is shown in Figure 1. Based on topography and storm sewer inlets, the entire study area is divided into 81 sub-areas that range in size from 0.01 to 1.4 hectares.

Table 2 - Mix of Land Uses in Happy Hectares

Land use	Area, m^2	Area, sq. ft.	Area, acres	Units
Apartment	20,743	223,272	5.13	2
Commercial	52,457	564,645	12.96	6
LD Residential	71,294	767,401	17.62	51
MD Residential	168,303	1,811,599	41.59	259
ROW	105,382	1,134,319	26.04	29
School	24,044	258,802	5.94	1
Total	442,222	4,760,038	109.28	348

Figure 1 - GIS Coverage for Happy Hectares



Developed spatial databases are saved as shape files that are summarized below.

- HHs: Entire Happy Hectares based on sub-drainage areas (433 sub-areas)
- Lots: Data for private lots (330 lots)
- ROW: Data for the public right of way (29 ROW segments)
- Buildings: Building coverage (344 buildings)
- Driveways: Driveway coverage (283 driveways)
- Sewers: Storm sewers (81 sewer pipes)
- Manholes: Storm sewer inlet manholes (82 manholes)
- Contours: One meter topographic contours

Land Use Analysis for Stormwater Drainage Modeling

For stormwater drainage analysis, the entire Happy Hectares can be modeled as one single subcatchment, 11 subcatchments based on the main sewer trunks, 81 subcatchments based on all drainage inlets, and so on (see Table 3). Some of the land use analyses for stormwater drainage study were built in the relational database as queries. Several built-in queries for land use analysis are listed in Table 3.

Table 3 - Built-in Queries for Land Use Analysis

Query	Subcatchments	Description
SubC_001	1	entire area
SubC_003	3	soil properties
SubC_006	6	land use categories
SubC_011	11	main sewer trunks
SubC_025	25	street names
SubC_027	27	sewer branches
SubC_081	81	storm inlets
SubC_348	348	parcels

The query result determines total area (Area), total impervious area (TIA), directly connected impervious area (DCIA), and pervious area (PA) for every subcatchment of the Happy Hectares. One example is shown in Table 4 from a built-in query titled "SubC_011".

PRECIPITATION DATA ANALYSIS

Long-term precipitation data is one of the most important data sets in urban stormwater analysis. A design storm (intensity, duration, and frequency), traditionally used for designing stormwater infrastructure, can be derived from the analysis of this long-term precipitation data. While precipitation data are very critical, it is difficult to obtain suitable data sets that have long record histories and enough resolutions in monitoring interval and depth. Hydrologic response time, e.g., the time of concentration, is much faster in urban areas. Thus, small time step precipitation data is essential for performing continuous simulation and developing intensity-duration-frequency (IDF) curves to derive design events.

Table 4 - Land Use Analysis Based on the Main Sewer Trunks (m^2)

Node	Area	TIA	DCIA	PA
A000	45,012	14,144	7,047	30,868
B000	70,968	25,676	15,645	45,293
C000	25,748	19,244	14,657	6,505
D000	44,657	16,844	10,240	27,812
E000	39,759	13,484	7,748	26,274
F000	16,319	5,344	3,129	10,975
G000	71,092	30,472	20,281	40,620
H000	59,685	30,736	24,018	28,948
I000	6,713	5,226	4,775	1,486
J000	32,400	18,707	14,967	13,693
K000	29,871	27,277	26,866	2,594

NCDC Precipitation Data

Local precipitation data can be obtained from National Climatic Data Center (NCDC) CDs or downloaded directly from their website (www.ncdc.noaa.gov). Hourly and 15-minute data sets are available for most areas of the United States. Better local data may be available in some areas. Much of the NCDC's hourly data have been monitored since the 1940s and its 15 minute data since the 1970s. These data are reported in 0.01 or 0.10 inch increments.

Each record of the NCDC precipitation data includes station number, start time, depth, and a flag based on data status. There are three kinds of flags for a record: A-accumulating, M-missing, and D-deleting. If there is no flag, the record is a well-monitored data point. Several steps of data pre-treatment, which are required for further analysis, are summarized below.

- Step 1. Select a period of good data: If there are too many flags within a certain period, it should not be selected.
- Step 2. Clean flagged data: The flagged data need to be cleaned to make a good data set for further analysis. A reasonable way to do it is to delete all flagged data. Data with "A" are accumulating values during several time steps, and data with "M" or "D" are all zero values.
- Step 3. Convert start time: Text formatted start time for each record needs to be converted into a real number format.

Three fundamental precipitation data analysis methods were developed using spreadsheet and Visual Basic for Applications (VBA) as programming tools. The developed methods include event-based synoptic analysis, a precipitation disaggregation procedure for shorter time steps and smaller pulse depths, and IDF analysis with disaggregated data.

Event-based Synoptic Analysis

Synoptic analysis is an event-based statistical analysis of long-term precipitation data. A spreadsheet version of synoptic analysis was developed in this project. It is similar to the SWMM Rain module and EPA's Synop software. Rainfall events are separated by a certain amount of dry time, i.e. no rain for that period. This dry period for defining a storm event is called minimum interevent time (MIT) (Huber and Dickinson 1988) or inter-event time definition (IETD) (Adams and Papa 2000).

Disaggregation Procedure

Several approaches to disaggregate hourly precipitation data to shorter time steps have been developed (Ormsbee 1989; Durrans et al. 1999; Burian et al. 2000; Burian et al. 2001). Ormsbee (1989) proposed continuous deterministic and stochastic disaggregation models and the others presented a polynomial-based approach and artificial neural network based models. Ormsbee's continuous deterministic disaggregation procedure was applied in this project because most of the other methods require training or sample data sets with smaller time steps for selecting required model parameters. The basic assumption of this method is that the distribution of precipitation within a time step is proportional to the distribution of precipitation over the three-time step sequence to include the adjacent before and after time steps (Ormsbee 1989). Based on this linear assumption, precipitation data can be disaggregated into smaller time steps and pulse depths.

IDF Analysis

In design event approaches, a design storm can be selected from the local IDF curves for a specified time of concentration (or duration) and return period. A local IDF curve may be available, but it may exclude either shorter durations (e.g. less than 60 minutes) or more frequent events (e.g. less than 2 year return period). Frequent small storms with short durations and return periods are very important for urban stormwater management because of the fast hydrologic response time in urban areas. For this reason, an IDF analysis procedure for shorter time intervals and rainfall pulses was developed. The 1-hr or 15-min NCDC precipitation data must be disaggregated before performing IDF analysis.

The empirical return period is calculated by the same general equation (Gringorten 1963; Cunnane 1978) used in the SWMM Rain block (Huber and Dickinson 1988):

$$Ret = (Yrs + 1 - 2A) / (Rnk - A) \qquad (2)$$

Where Ret = return period in years; Yrs = number of years of data; Rnk = rank of event (ranked in descending order); and A = parameter for plotting position.

A value of 0.4 for parameter *A* was suggested as a good compromise for US customary units by Cunnane (1978) and this value has been adopted for this IDF procedure.

Finding Optimal Parameter Estimates for IDF Curves

It is convenient to replace IDF curves with an equation that accurately represents them. Two questions need to be addressed:

1. what form of equation should be used; and
2. what are the best parameter estimates for this equation?

A variety of return periods can be fit into a single equation of the form using the Solver optimization procedure:

$$i = \frac{a + b\ln(r)}{(t + c)} \qquad (3)$$

Where i = average intensity (in/hr); r = recurrence interval (yrs); and a, b, c = parameters.

TIME-AREA CONCEPT RUNOFF ROUTING MODEL

To develop the entire hydrograph, Ross (1921) described the time-area (TA) method using isochrones, i.e., lines of equal travel time of a drainage area. The areas between adjacent isochrones are measured to create the time-area histogram, and the rainfall intensities within successive time increments are averaged. The Rational Method is then applied for each area and each time increment to develop the entire combined hydrograph. The time-area method has been applied to several models in analyzing urban hydrology – e.g., TRRL (Watkins 1962), ILLUDAS (Terstriep and Stall 1974), ILLUDAS-SA (Watson 1981), and ILSAX (O'Loughlin 1986).

Limitations and Improvements

The time-area (TA) method does not account for storage and dispersion effects. As a result, hydrographs calculated by the TA method show higher peaks than those that consider storage. This is the main reason that TA related techniques are considered to be applicable only for small to mid-sized catchments (Stall and Terstriep 1974; Ponce 1989). Whether a catchment is small can be determined by its physical size and the relationship between time of concentration and rainfall duration. Ponce (1989) characterized a small catchment as follows:

- A catchment with a concentration time of 1 hour or less, or a catchment with an area of less than 2.5 km^2 (about 1 mi^2 or 640 acres).
- Storm duration (t_r) exceeds time of concentration (t_e): $t_r \geq t_e$
- Rainfall can be assumed to be uniformly distributed in time and space.
- Runoff is primarily by overland flow.
- Channel storage processes are negligible.

Storage and dispersion effects may occur more significantly within a channel rather than overland sheet flow. In order to model those effects, some flow routing models use a storage concept, such as level pool or linear reservoir routing technique, to perform flow simulation in channel or storm sewer systems along with the TA method for overland flow simulation. The Muskingum-Cunge method (Cunge 1969), which is one of the most popular methods in channel or stream flow routing techniques, can also be applied to either catchment or channel flow routing to account for storage and dispersion effects.

A more critical limitation of the time-area method is the time stationary problem due to a unique time-invariant flow transfer function. This limitation originated from one of the fundamental assumptions in the original TA concept. The unit hydrograph (UH) method, which was originally developed based on the TA concept and a hypothetical linear reservoir routing to account for storage effects (Clark 1945; ASCE-WEF 1992), has been applied to distributed runoff routing models using a raster-based digital elevation model (DEM) (Maidment 1993; Muzik 1996; Kull and Feldman 1998; Olivera and Maidment 1999). Those models, however, have the same time stationary problem and cannot account for time-variable rainfall intensity dynamics. Saghafian et al. (2002) present a runoff hydrograph simulation model based on the time variable isochrone technique. They describe it as a distributed model in space and time. It includes spatial and temporal variations of rainfall intensity and spatially variable catchment characteristics using raster-based Geographic Information Systems (GIS), mainly a digital elevation model (DEM). A number of time-area histograms were derived based on excess rainfall intensities, and then applied separately to derive individual outflow hydrographs for each rainfall pulse. For derivation of the overall hydrograph, individual hydrographs are overlapped and integrated throughout time. This time variable isochrone technique alleviates a major constraint from the conventional TA method.

Estimation of Time of Concentration

In applying the time-area method, the estimation of time of concentration or subcatchment flow travel time is the most critical procedure. In small catchments, overland flow can be assumed to be an outflow from a rectangular plane with averaged flow length, slope, and width. Travel time is a function of surface roughness, slope, overland flow length, and rainfall intensity. If high-resolution spatial and rainfall data are available, travel time can be confidently estimated. Several empirical equations have been introduced to estimate travel time and/or time of concentration. The kinematic wave equation that was introduced by Morgali and Linsley (1965) has been widely used to estimate overland flow travel time (Aron and Erborge 1973; Chow et al. 1988; Muzik 1996; Molnár and Julien 2000). It can be obtained from the Saint-Venant equations and the Manning resistance equation (Woolhiser 1977; Saghafian and Julien 1995). It is applied to this study and can be expressed as follows (ASCE-WEF 1992):

$$t_e = C_t \frac{L^{0.6} n^{0.6}}{i^{0.4} S_o^{0.3}} \qquad (4)$$

Where t_e = time of concentration (min); C_t = unit constant (6.99 for SI units and 0.938 for US customary units); L = overland flow length (m or ft); n = Manning's roughness coefficient; i = rainfall intensity (mm/hr or in/hr); and S_o = average overland slope.

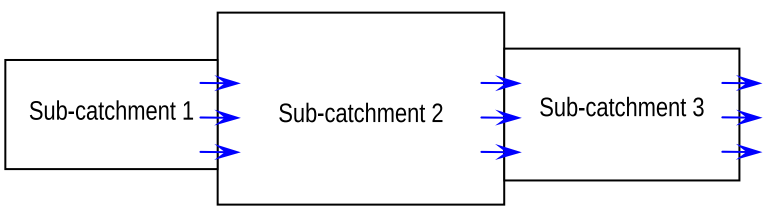
Developing a Time-Area Histogram

A time-area histogram can be developed using isochronal lines that are placed on a catchment map. Placing accurate isochronal lines is the most critical procedure in the conventional TA, but it is not an easy task. It can be performed more accurately and easily using GIS techniques, but most of the applications have been developed using raster-based data. In this study, a time-area histogram is developed based on a cumulative time-area relationship instead of using physical isochronal lines or distributed grids. Flow travel time for each sub-catchment is estimated by the kinematic wave equation. The start time of runoff contributing from a sub-catchment is estimated from the sequence of cascading planes. The start time is the sum of all travel times of the planes between the sub-catchment and the connected storm inlet. If the flow travel time of the sub-catchment is added to this start time, it becomes the end of runoff contributing time for the sub-catchment. Based on these start and end times of contributing runoff for cascading sub-catchments, a cumulative time-area diagram can be developed for the entire catchment. A time-area histogram for any isochronal time increments (Δt) can be derived from this cumulative TA diagram. This procedure is described in Figure 2 and a net runoff contributing area for each isochronal time step can be calculated as follow:

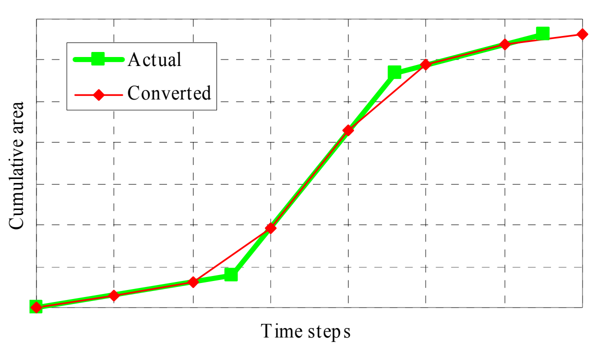
$$A_i = \sum_0^i A - \sum_0^{i-1} A \qquad (5)$$

Where A_i = net runoff contributing area for the time step *i*; and $\sum A$ = cumulative runoff contributing area.

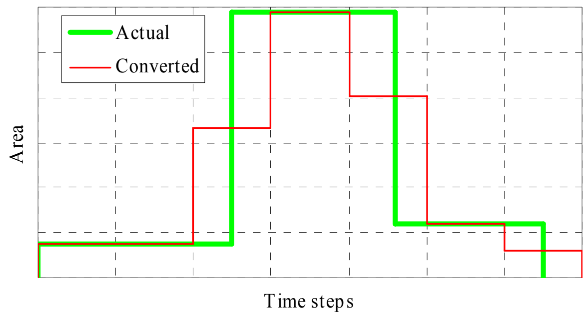
Figure 2 - Development of a Time-Area Histogram Using Cascading Planes



(a) Cascading sub-catchments



(b) Cumulative time-area diagram



Actual: based on the actual time of concentration for each sub-catchment
Converted: converted for every time step

(c) Time-area histogram with equal time increments

OPTIMIZATION OF FUNCTIONAL LAND DEVELOPMENT STRATEGIES

Sample et al. (2001) presented a linear programming (LP) model to find the combination of functional land use options that minimizes the total cost of providing the required amount of roof, driveway, yard, and patio while satisfying the requirements for on-site depression storage at a residential lot. However, this model is not able to handle other hydrologic functions that can represent the performance of various distributed wet-weather flow control alternatives such as peak discharge, total runoff volume, and flow travel time or time of concentration. These criteria are important for designing urban stormwater management systems and need to be included in optimization models to represent process constraints more accurately. To include them, a stormwater rainfall-runoff simulation needs to be performed within the optimization procedure.

Maximizing on-site stormwater management is the key concept of the new approaches of distributed wet-weather flow controls (WWCs). These approaches are usually expressed as follows:

1. Maximize on-site depression storage and infiltration and minimize runoff discharge.
2. Minimize directly connected impervious area (DCIA).
3. Maximize flow paths and time of concentration.

Using a lumped simulation model and/or spatial information, it would be very difficult to evaluate their physical performance. An alternative optimization system is developed based on a lot-level functional spatial database and time-area concept flow routing techniques. Functional land development options can be evaluated using multiple constraints for rainfall-runoff parameters within distributed WWCs: depression storage, peak discharge, runoff volume, and time of concentration. Depression storage is modeled linearly, as is that in Sample et al. (2001). To estimate peak discharge, the Rational Method is applied with a new approach of estimating a runoff coefficient. It is based on depression storage and infiltration rate for each functional land use option as follows:

$$Q_p = C\, i_e\, A \qquad (6)$$

$$C = \frac{\sum C_j A_j}{A} \quad (7)$$

$$C_j = \frac{(i - f_j)\, t_e - DS_j}{i\, t_e} \quad (8)$$

Where Q_p = peak discharge [L^3T^{-1}]; C = area-weighted runoff coefficient; i_e = excess rainfall intensity [L T^{-1}]; A = catchment area [L^2]; i = total rainfall intensity [L T^{-1}]; j = functional sub-areas; f = infiltration rate [L T^{-1}]; t_e = time of concentration [T]; and DS = depression storage [L]. (Note: DS = 0 in the worst-case scenario.)

The time-area method is able to develop the entire hydrograph and estimate the peak discharge and time of concentration. Travel time for each sub-area is estimated using a kinematic wave equation (ASCE-WEF 1992) and area-weighted roughness coefficients as follows:

$$t_e = C_t \frac{L^{0.6} n^{0.6}}{i_e^{0.4} S_o^{0.3}} \quad (9)$$

$$n = \frac{\sum n_k A_k}{A} \quad (10)$$

Where t_e = time of concentration (min); C_t = unit constant (6.99 for SI units and 0.938 for US customary units); L = overland flow length (m or ft); n = Manning's roughness coefficient; i_e = excess rainfall intensity ($i_e = i - f$) (mm/hr or in/hr); S_o = average overland slope; and k = land use option for the functional sub-area.

Using the above process models, a distributed land development optimization model is organized as follows:

$$\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} C_i^j A_i^j \quad (11)$$

$$\text{Subject to } \sum_{j=1}^{n} A_i^j = A_i \quad (12)$$

$$\sum DS_i^j A_i^j \geq S \quad (13)$$

$$Q_p^{estimated} \leq Q_p^{target} \quad (14)$$

$$t_e^{estimated} \geq t_e^{target} \quad (15)$$

Where Z = total cost; i = functional sub-areas; j = functional land development options; C_i^j = unit cost of option j for sub-area i; A_i^j = area of option j for sub-area i; DS_i^j = depression storage of option j for sub-area i; S = required on-site depression storage; *estimated* = model estimated value; and *target* = design target value.

Two more process constraints are added to the existing model (Sample et al. 2001). Other design criteria can also be added to the above model. A reasonable value of target time of concentration needs to be arranged based on a general intensity-duration relationship as follows:

$$i = \frac{a}{t_r^b + c} \qquad (16)$$

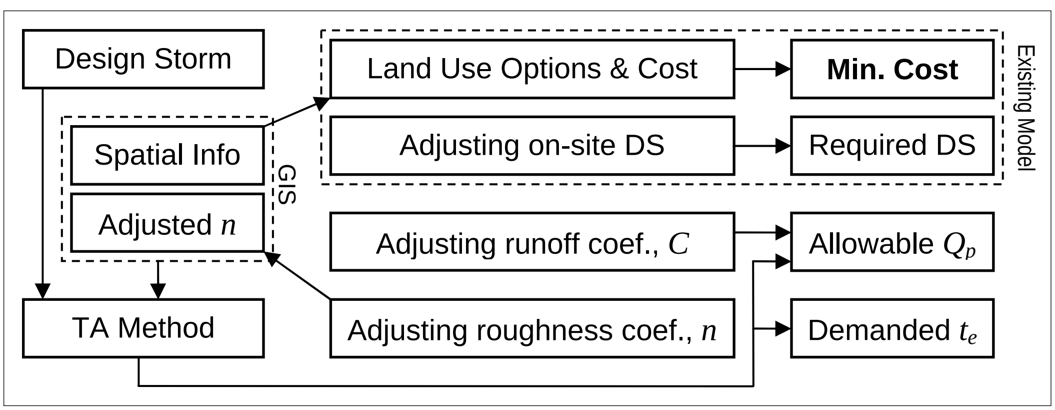
Solving equation (16) for t_r yields:

$$t_r = \left(\frac{a}{i} - c\right)^{1/b} \qquad (17)$$

Where i = design rainfall intensity; t_r = rainfall duration (min); a = constant varying with location and return period; and b and c = constants varying with location but independent of return period.

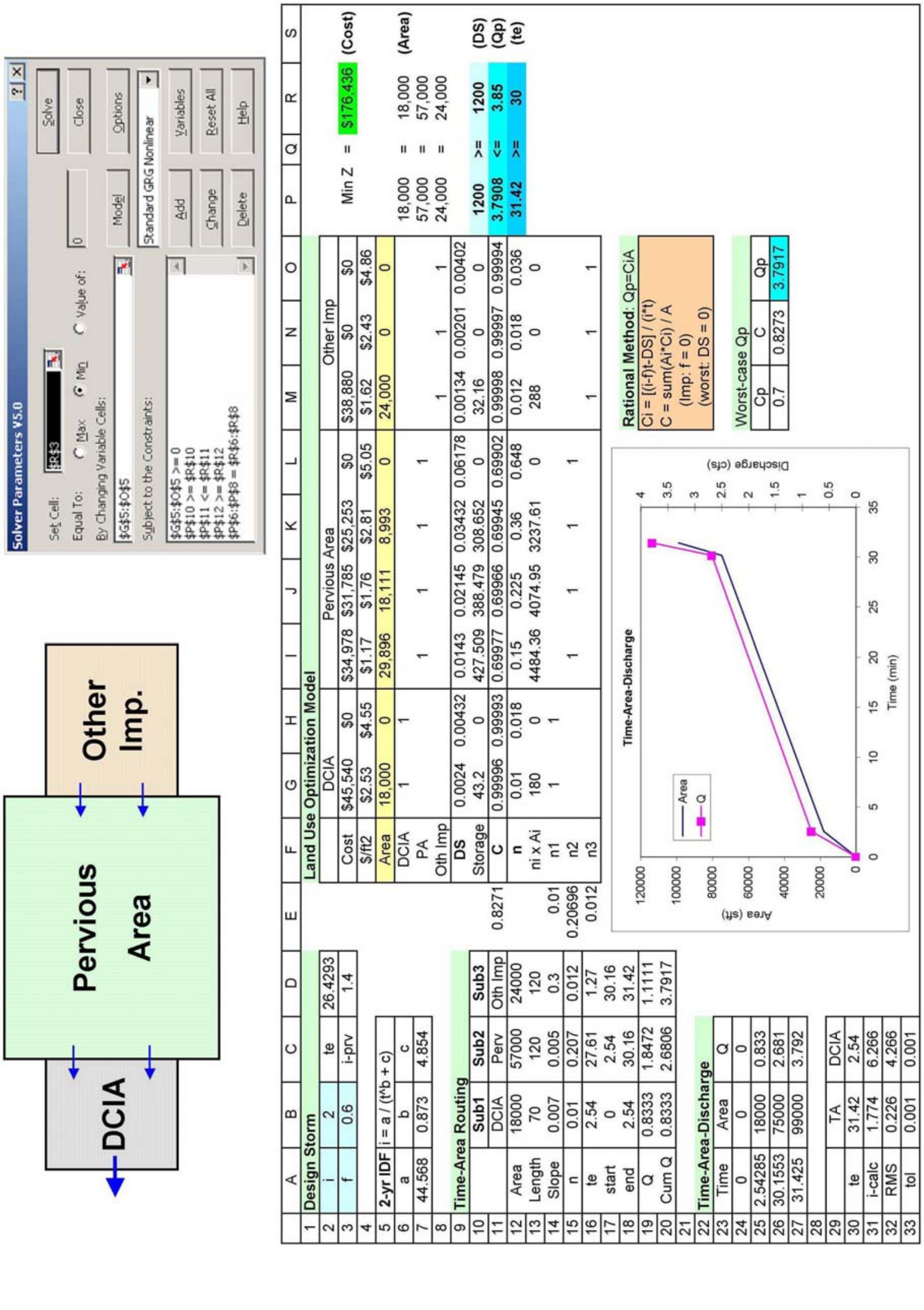
The framework of this optimization model for functional land development strategies is shown in Figure 3. It consists of functional land use information from spatial analysis, design storms from the IDF analysis, time-area concept flow routing, and cost estimation. It includes modeling depression storage, roughness coefficient (*C*), runoff coefficient (*n*), time-area method flow routing, intensity-duration relationship, resulting peak discharge, and time of concentration. Process characterization relationships and performance criteria throughout the optimization procedure are significantly improved compared to the existing LP model, which only considered initial depression storage (Sample et al. 2001). These modeling components can be assembled and integrated with optimization tools within a spreadsheet.

Figure 3 - Optimization Framework for Functional Land Development Strategies



An example of the developed spreadsheet optimization model is presented in Figure 4. This model was solved by the standard nonlinear programming generalized reduced gradient solver in Excel to find the most cost-effective solution. The existing simple land use optimization model is extended to include two more important process constraints: peak discharge and time of concentration for evaluating the performance of distributed stormwater management strategies.

Figure 4 - Distributed Land Development Optimization Model Based on a Design Storm Approach



As described in equations (6) through (8), the peak discharge can be estimated using an area-weighted runoff coefficient. In this model, the runoff coefficient is derived directly from the surface physical parameters: infiltration rate and depression storage of every functional sub-area. Depression storage can be assumed as zero to estimate the worst-case peak discharge. Time of concentration is estimated using the time-area concept process simulator (see the upper left part of Figure 4). Flow travel time for each sub-area is adjusted by different surface roughness options. An adjusted roughness coefficient for each sub-area is obtained directly from the functional land use simulation model through an area-weighted approach (see the upper right part of Figure 4). Increasing time of concentration can also be achieved by adjusting flow directions from one sub-area to other sub-areas. It is easily modeled using the time-area process simulator by adjusting outflow directions and/or bottom slopes. This kind of implementation for urban wet-weather flow control is one of the most important directions in the Low Impact Development (LID) concept for urban development. If necessary, the time-area simulator can create the entire hydrograph to evaluate a comprehensive performance, including the peak discharge, the total runoff volume, and detailed temporal responses. It can be done with reasonable effort and still in an explicit manner.

SUMMARY AND CONCLUSIONS

The purpose of this paper is to provide an overview of a research project funded by US EPA and describe an optimization method for finding cost-effective solutions to urban wet-weather flow problems. The entire optimization decision support system (ODSS) is developed as a series of SS files.

A hierarchy of spreadsheet-based process simulators has been developed as part of the project. These simulators provide flexibility in formulating the optimization problem. Options are presented for land use, rainfall, dry-weather flow, depression storage and infiltration, evapotranspiration, pollutant generation, overland flow routing, channel routing, and storage/treatment.

Major advances in our ability to evaluate urban wet-weather flow systems have come about because of having high quality GIS and associated database information that allows us to evaluate and optimize WWCs at various levels of aggregation that are infeasible without such tools. A major effort of the project has been to compile a high quality GIS and associated database for Happy Hectares. Hydrologic response time, e.g., the time of concentration, is much faster in urban areas. Thus, small time step precipitation data is essential for developing IDF curves to analyze single design events, and to perform continuous simulation. Three basic precipitation data analysis methods have been developed using spreadsheet and VBA. The three models consist of an event-based synoptic analysis, a continuous disaggregation procedure, and a method for developing IDF curves. These models can be integrated into any spreadsheet optimization procedures.

Land use options for wet-weather control are jointly optimized with decentralized on-site controls by linking the optimizers to developed analysis models. This effort is an extension of an earlier result wherein only land use options with off-site storage were considered (Sample et al.

2001, 2003). This model did not include other hydrologic functions that can represent the performance of various distributed wet-weather flow control alternatives, such as peak discharge, total runoff volume, and flow travel time or time of concentration. These criteria are important for designing urban stormwater management systems and need to be included in optimization models to represent process constraints more accurately. A design storm concept approach for functional land development optimization was presented in this paper. This integrated optimization model runs well in spreadsheet and can be solved by the SS-based nonlinear or evolutionary solver.

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