THE CASE FOR BETTER HYDROLOGIC MODELING METHODS

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INTRODUCTION

Water Environment Services (WES) of Clackamas County, Oregon, asked Pacific Water Resources, Inc. (PWR) to critically evaluate its surface water management program. Previously, Metro, the regional land use planning authority, opened significant new areas for development, effectively doubling WES' jurisdiction. After 10 years in operation the Agency desired an independent review of program results versus stated goals and objectives. Their aim was to determine existing program effectiveness prior to assuming jurisdiction over the new lands. In particular, WES wanted an evaluation of its quantity mitigation requirements. These requirements resulted in numerous small, unattractive and difficult to maintain detention facilities.

PWR's evaluation involved detailed analysis and review of a 235-acre pilot basin developed entirely under WES' jurisdiction. Field inventories showed consistent issues of stream erosion and bank instability. Some problems were related to poor design methods and standards such as improper riprap sizing and lack of effective energy dissipation structures. PWR's analysis also utilized a calibrated single-event hydrologic model (HEC-HMS) along with pipe hydraulics simulations (PC-SWMM) to evaluate the effectiveness of stormwater detention. These studies showed that traditional peak control design methods were inadequate for preventing downstream erosion and stream instability. As a result, PWR proposed a flow duration standard that, when implemented with appropriate design standards, should correct the erosion problems noted.

Experience with flow duration standards (as opposed to peak flow standards) in the Pacific Northwest shows that properly sized detention facilities require greater volume than traditional designs. Added volume creates adverse economic impacts on development thus limiting acceptance by regulatory agencies and the public. In addition, existing flow duration analysis methods used in Washington State tend to be more regional in application. They lack adaptability to specific basin areas or watershed management objectives. These limitations have, in part, slowed acceptance of continuous hydrologic modeling methods in Oregon.

In response to these concerns and input from clients, PWR developed a continuous hydrologic modeling tool that permits adaptation to specific watersheds and even subbasin areas. The model includes options for supporting explicit watershed management goals and allows more or less protection, as appropriate, for receiving waters. In addition, the model gives users the ability to directly simulate several different low impact development (LID) techniques, either alone or in combination. This approach provides designers a tool for comparing costs of various stormwater management techniques. Because LID emphasizes stormwater infiltration, it reduces runoff and, therefore, required detention volume.

PILOT BASIN STUDIES

The full scope of work desired by WES involved developing consistent single-event models for its entire jurisdiction and the expansion areas, nearly 40 square miles. A comprehensive and detailed evaluation of the existing stormwater runoff program's performance required a much greater level of detail than was possible for this entire study area. The required level of detail would involve complete inventories of existing stormwater infrastructure, intensive modeling of most collection system hydraulics, and explicit simulation of all existing stormwater detention facilities. This effort also required time to evaluate and carefully review model results and to develop additional modeling scenarios if necessary.

The solution was to perform an intensive study of one specific basin developed entirely under the WES surface water management program. The 235-acre pilot basin was selected for its similarity to the expansion areas with rolling terrain and moderate slopes. It was bisected by a major stream, Mt. Scott Creek, and included a few minor tributaries draining discrete subbasin areas. Except for greenways along the creeks, the basin was completely developed as single family detached housing with an approximate density of 4-6 units per acre. This approach assumed that issues encountered within the pilot basin were reasonably representative of other developments constructed under WES jurisdiction, and that future developments constructed in similar terrain would yield similar results.

Information available for the pilot basin analysis was similar to that used throughout the overall study area and facilitated the use of GIS techniques. Data layers included high resolution aerial photographs, soils and land use delineations, and 2-foot contours with impervious area mapping developed using LIDAR. PWR's hydrologic analysis began with a thorough review of the Agency's design rainfall depths and storm distribution. It included development of a new 72-hour design storm intended to be more representative of local storm events. In addition, WES provided record drawings and drainage reports for all pilot basin subdivision developments. This information, along with the consequences of system performance, was field verified by PWR.

HEC-HMS was used for all hydrology estimates. Subbasins throughout the entire 40 square mile study area were delineated down to typically about 100-200 acres, except for the pilot basin where they were much smaller. The model was calibrated to two different study area stream gages. Problems with the hydrograph recession limb required implementing the HMS soil moisture accounting (SMA) module. Using SMA, recession limb results were substantially improved and calibration parameters were finalized.

Pilot basin subbasin areas averaged about 10 acres in order to capture and simulate specific detention basin drainages. Again, HEC-HMS was used for all hydrology ensuring pilot basin consistency with the overall study area. PC-SWMM was used only to simulate pipe hydraulics and route stormwater runoff through detention facilities to downstream receiving waters. A total of nine detention basins, five above ground and four below, were simulated using PC-SWMM along with over 20 additional subbasin areas.

After calibrating the overall study area hydrologic model, a "predevelopment" scenario was necessary to establish a baseline hydrologic response prior to development. Historic aerial photographs were obtained from the local US Army Corps of Engineers showing watershed conditions as far back as the 1930s. At that time, over 70 years ago, the entire study area was already converted from forest to farming and grazing. The predevelopment scenario was created using impervious area measurements from these historic photos showing predominantly agricultural land uses. In addition, appropriate subbasin timing revisions were made to reflect significantly less effective impervious area. The result was a "calibrated" predevelopment model, effectively demonstrating basin runoff response prior to present day conditions.

As noted earlier, PWR field verified record drawings showing pilot basin improvements. All stormwater related facilities substantially matched the records provided. A few underground detention structures were observed to be in permanent overflow operation because of sediment accumulations that restricted their outlets and storage volumes. A lack of energy dissipation structures or appropriately sized riprap at pipe outlets contributed to erosion related problems on the moderate slopes. PWR also reviewed the hydrology design reports provided for each of the dozen or so developments constructed within the pilot basin. This documentation showed a wide range of engineering competency with no major blunders or errors encountered.

In part, the channel erosion and bank instability noted may be attributed to the flashy hydrology caused by new impervious surfaces on the watershed. Increased watershed erosion contributes to a physical imbalance of sediment transport and habitat degradation in receiving waters. Previous Pacific Northwest studies indicated a threshold value of about 10% impervious area, above which degradation of aquatic resources typically occurs. (*Effects of Urbanization on Small Streams in the Puget Sound Ecoregion*; May, Horner, Karr, Mar, Welch; Watershed Protection Techniques. 2(4):483-494.) Mapped impervious area in the pilot basin was estimated using LIDAR to be nearly three times this value.

The purpose of detention facilities is to mitigate peak runoff and protect downstream areas. Model results showed that detention facilities consistently discharged 2-3 times the allowable peak flow based on use of the calibrated predevelopment model. Figure 1 shows a typical three-day simulation of one pilot basin detention pond with a contributing drainage area of 5.44 acres. When this particular basin was constructed, the WES standard required matching a 25-yr developed condition peak flow to the 5-yr predeveloped condition. Figure 1 illustrates a 25-yr peak inflow of about 2.5 cubic feet per second (cfs) reduced to about 0.9 cfs outflow. This outflow, however, represents nearly twice the allowable discharge of about 0.5 cfs. Figure 1 also illustrates that detention pond outflows exceeded predevelopment conditions for almost 2 days during the three-day design storm (see the shaded area).

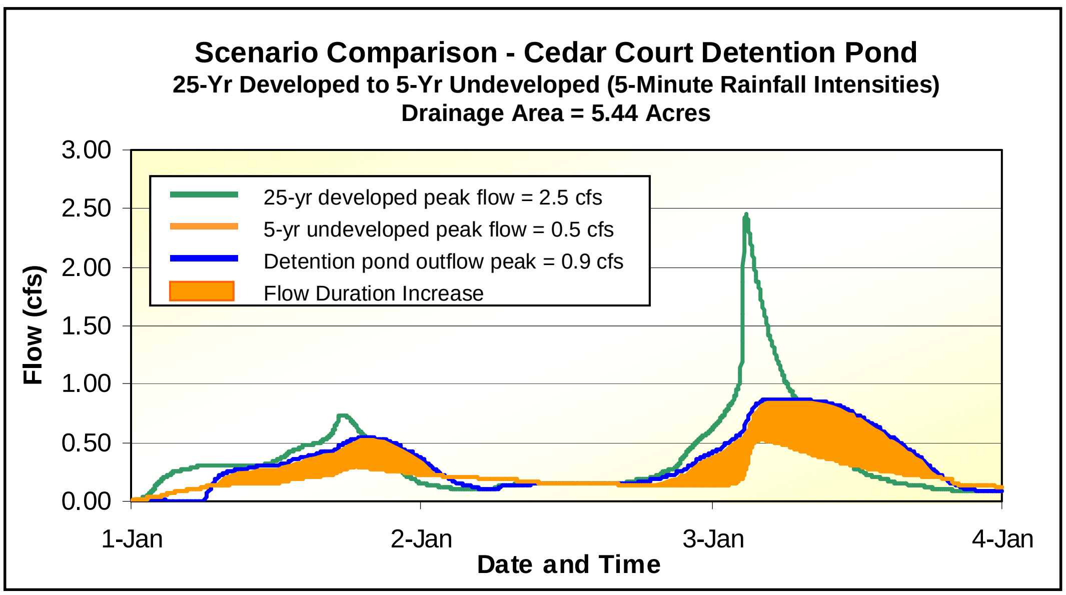


Figure 1 - Typical Pilot Basin Detention Facility Performance

All pilot basin detention ponds significantly exceeded allowable peak discharge rates in effect at the time of design. This fact indicates a flaw with the design methods used for sizing detention facilities. Traditional designs are performed at a site level without benefit of a calibrated watershed model. Typically, a Soil Conservation Service (SCS) 24-hour hydrograph is used for the analysis procedure. The SCS method was originally developed for sizing conveyance facilities on large agricultural watersheds. It was intended to be conservative since a slight increase in pipe size or channel area was not viewed as adverse to project economics. Today's regulatory environment, however, includes Clean Water Act (CWA) and Endangered Species Act (ESA) requirements. Use of methods that consistently fail their intended purpose suggests a need to adopt more appropriate design techniques.

Oversizing pond outlets is not the only weakness of traditional analysis methods. Figure 1 also shows that the absolute peak of the developed condition detention discharge was substantially "stretched out" from about half a day to more than one day. This peak stretching phenomena allows the peaks of multiple detention ponds to overlap, thus reducing their effectiveness downstream. Figure 2 shows the entire 235-acre pilot basin both with and without detention facilities. Removing all detention facilities from the pilot basin resulted in a peak flow increase of about 10%. The additive effect of multiple detention pond peak stretching was also observed by Emerson, Welty and Traver. (*Watershed Scale Evaluation of a System of Storm Water Detention Basins*, Emerson, Welty and Traver: Journal of Hydrologic Engineering, ASCE, May/June 2005.) And, for the pilot basin as a whole, the actual detained peak is more than three times the allowable predevelopment discharge.

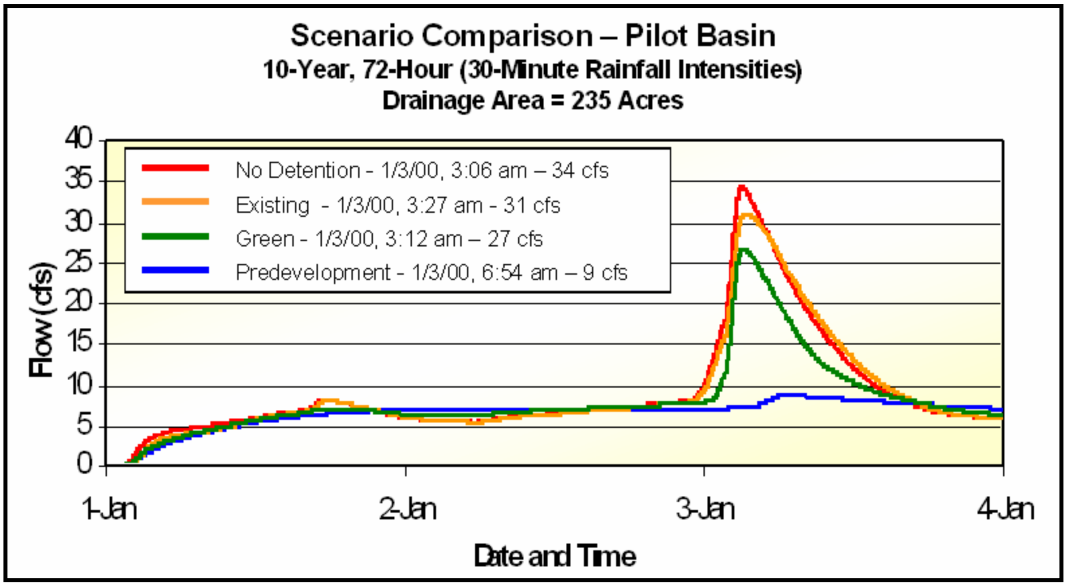


Figure 2 – Performance of Multiple Detention Ponds in the Pilot Basin

Figure 2 also shows results of a "Green," or LID, scenario for the pilot basin in which total impervious area was reduced by 10%. This reduction is not unreasonable given studies by Pierce County, Washington, which suggest that impervious area reductions on the order of 20% are achievable. (*Pierce County Low Impact Development Study*, prepared for Pierce County, April 11, 2001 by CH2M-Hill.) Basin timing was appropriately increased to reflect greater use of sheet flow and less effective impervious area. This scenario also removed existing detention facilities and assumed greater soil moisture storage in lawn and landscape areas by modeling 10 inches of stable soil amendments (e.g. mature leaf compost). The result was a 20% decrease in peak flow over the "No Detention" case or about twice the benefit of detention. This suggests that LID techniques may be more effective than detention alone for reducing peak runoff from developed areas.

RECOMMENDATIONS FOR IMPROVED HYDROLOGIC MODELING METHODS

The pilot basin studies showed that traditional site-based detention sizing using a *peak flow* standard consistently oversizes flow controls. Oversized flow controls result in undersized storage mitigation volumes. In addition, Figure 1 shows that almost no detention is provided for storms less intense than the design event. During most of the simulation's first day, developed conditions flow exceeded predevelopment conditions. This suggests that smaller, more frequent storm events rush through these detention facilities with all the energy imparted by impervious surfaces and no peak flow mitigation. Then, high-flow periods produced by the stretched out third day peak add more stress to channel banks and beds. The result is increased erosion and the channel instability noted during PWR's field observations.

In the 1990s, King County, Washington implemented a *flow duration* standard utilizing continuous hydrologic modeling methods for site-level evaluation of development impacts. Known as KCRTS, this analysis method, based on a calibrated continuous hydrologic watershed model, substantially improved our understanding of the hydrologic response due to development within King County. However, its one-size-fits-all approach was necessarily limited to that specific geographic area. Subsequent models developed for Washington's Department of Transportation (DOT) and Department of Ecology (DOE) ignored differences at the subbasin level in favor of a more regional standard. PWR's work in Southwest Washington found that regional parameters used in DOE's Western Washington Hydrology Model did not calibrate well to stream gages available in our study areas.

From these experiences PWR developed a continuous hydrologic modeling application for use in Northwest Oregon. This site-based, calibrated watershed modeling tool differs from the Washington models in several respects. While it uses pre-simulated runoff time series (like KCRTS), modeling simulations can be varied on a subbasin by subbasin basis to reflect differences in rainfall, slope, or other physical parameters. For example, across the urbanized portions of the Tualatin Valley (west Portland metropolitan area), average annual rainfall ranges from 38-58 inches within 20 miles. Soils vary from hydrologic soil group C to D. Elevation ranges from 150-1500 feet (MSL). Such variations must be accommodated by the modeling approach or significant errors result.

The flow duration design model (FDDM) developed by PWR accommodates application to specific subbasin areas by containing numerous runoff time series. Each runoff simulation was developed from one consistent continuous hydrologic model (HSPF) calibrated for various land uses to numerous gages throughout the basin. Drop-down lists allow the user to select both the basin and subbasin areas for use in the analysis. Based on these selections the program utilizes the appropriate subset of pre-stored unit-runoff simulations (i.e. runoff time series). If no calibrated simulations are present the model interpolates between the appropriate data sets.

This approach also permits adapting the model to specific watershed management goals. With basin and subbasin specific values, jurisdictions can adjust "target" outflow conditions based on actual aquatic resource values. For example, subbasin areas higher up in a watershed may have better receiving water quality and thus greater resource value. For this particular subbasin area the jurisdiction may set a target developed conditions outflow at, say, 10% imperviousness. Exceeding this imperviousness would require developers to construct mitigation designed to a flow duration standard. Further down in the valley aquatic resource value may be already impaired, justifying higher target outflow conditions, say 20% impervious area. The FDDM calculates target outflow conditions at the subbasin level based on allowed imperviousness established by the jurisdiction.

Basin and subbasin specific modeling can be used to set design performance thresholds. For example, higher value aquatic resource areas may warrant control of larger storms than subbasins with already severely degraded aquatic resources. Control of 25-year, or even larger storm events, may be appropriate in high value areas while lower value areas may only justify control of a 10-yr storm. Conversely, low range thresholds can be set based on soils and their erosive potential. In some soils the threshold channel forming flow may be a 1.1-yr storm while in others it may be a 1.5-yr storm. Figure 3 illustrates the use of performance thresholds. In this case the lower threshold (light blue horizontal line) is set at ½ the 1930s condition 2-yr peak flow. The upper threshold (orange horizontal line) is set equal to the 1930s condition 10-yr peak flow. Vertical index lines are also used to indicate the probability of threshold flows by their intersection with the target flow duration curve.

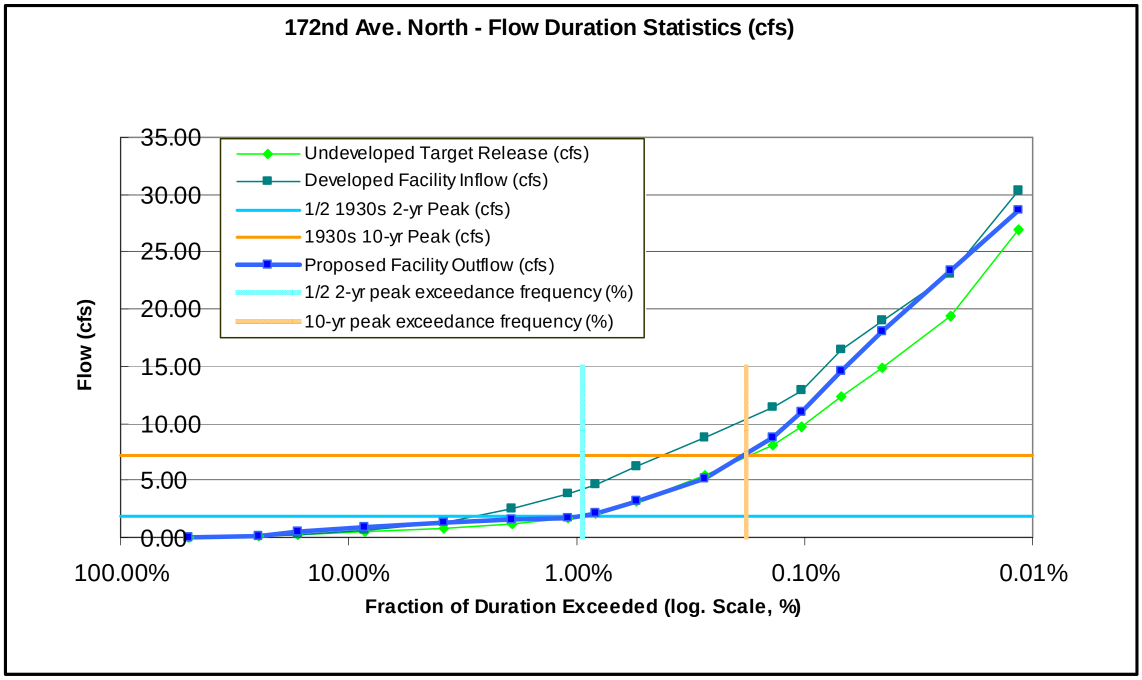
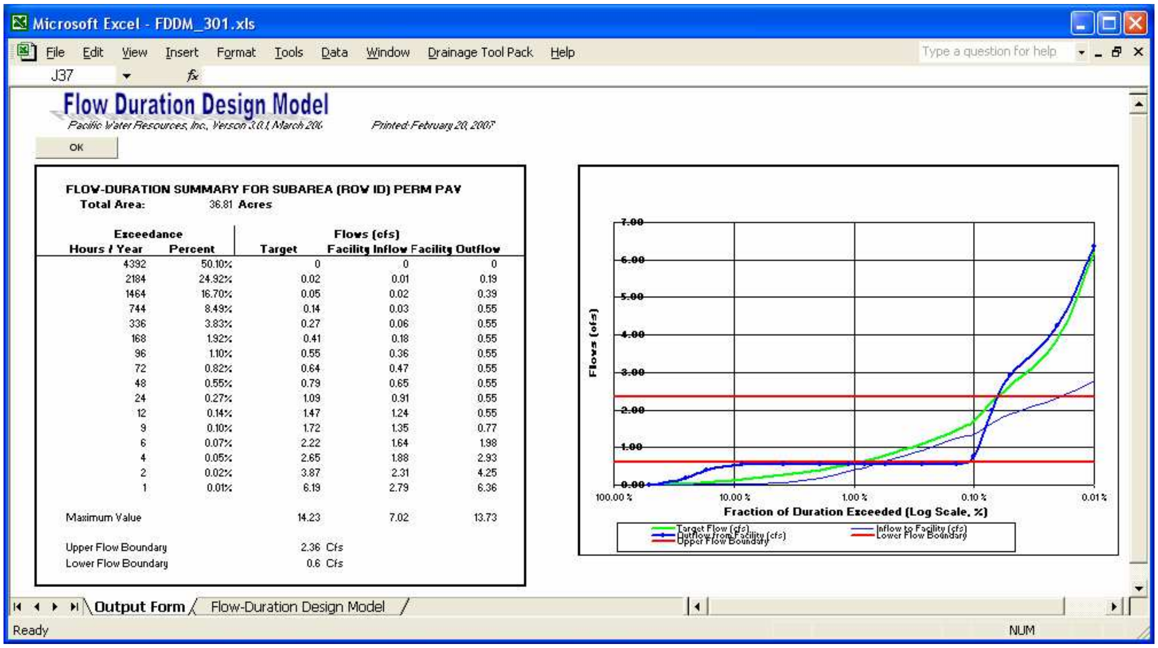


Figure 3 – The Flow Duration Design Model Showing Performance Thresholds

Earlier it was noted that detention facilities designed to flow duration standards require greater volume than traditional designs. This is due, in part, to the fact that continuous modeling using watershed calibrated models has much less tendency to oversize flow controls. Continuous modeling also considers the effects of back-to-back storms. And, flow duration standards typically require matching an entire range of storm discharges rather than a few discrete values. It was also noted that larger detention volumes have adverse impact on development economics. Therefore, the ideal modeling tool would allow designers the ability to evaluate multiple stormwater management scenarios such that they can be compared on a cost/performance basis.

The FDDM allows designers to explicitly simulate several low impact development (LID) techniques. Available options currently include green roofs, blue roofs, planter boxes, permeable pavements, amended soils, smart cisterns and traditional detention ponds. One or more facilities may be daisy chained to a common discharge point or different techniques may be utilized with separate discharge locations. Each technique can be optimized based on site constraints and development economics providing designers with a full pallet of tools. For example, a traditional residential development with detention can be compared to one using permeable pavements and soil amendments. Conceivably, LID tools can be combined to minimize, or in some cases even eliminate, the need for detention facilities. Figure 4 illustrates an optimized design for permeable pavement.



FLOW-DURATION SUMMARY FOR SUBAREA (ROW ID) PERM PAV
Total Area: 36.81 Acres

Exceedance		Flows (cfs)		
Hours / Year	Percent	Target	Facility Inflow	Facility Outflow
4392	50.10%	0	0	0
2184	24.92%	0.02	0.01	0.19
1464	16.70%	0.05	0.02	0.39
744	8.49%	0.14	0.03	0.55
336	3.83%	0.27	0.06	0.55
168	1.92%	0.41	0.18	0.55
96	1.10%	0.55	0.36	0.55
72	0.82%	0.64	0.47	0.55
48	0.55%	0.79	0.65	0.55
24	0.27%	1.09	0.91	0.55
12	0.14%	1.47	1.24	0.55
9	0.10%	1.72	1.35	0.77
6	0.07%	2.22	1.64	1.98
4	0.05%	2.65	1.88	2.93
2	0.02%	3.87	2.31	4.25
1	0.01%	6.19	2.79	6.36
Maximum Value		14.23	7.02	13.73

Upper Flow Boundary 2.36 Cfs
Lower Flow Boundary 0.6 Cfs

Figure 4 – FDDM Optimized Design for Permeable Pavement with Subgrade Storage

The approach used by the FDDM enhances regulatory efforts by supporting specific watershed management strategies. At the same time, this approach recognizes available watershed restoration technology, and local development economics, while providing better design performance than traditional methods. The FDDM can specifically consider the biological value or productivity of receiving waters at the subbasin level and impart an appropriate level of regulatory control. Concepts of flexible target outflows, regulatory thresholds and explicit LID modeling within a continuous hydrologic modeling tool provides jurisdictions an effective mechanism for implementing management strategies and enhancing overall watershed health.