4. TECHNICAL ANALYSIS OF HYDROMODIFICATION CONTROLS

4.1 INTRODUCTION

Under Provision C.3.f, *Limitation on Increase of Peak Stormwater Runoff Discharge Rates*, Dischargers (Co-permittees) must manage increases in peak runoff flow and increased runoff volume from certain new development and redevelopment projects so that post-project runoff does not exceed estimated pre-project rates and/or durations. This applies to conditions where the increased runoff from the project will result in increased potential for erosion or other adverse impacts to beneficial uses that are attributable to changes in the amount and timing of runoff.

How can increases in runoff peak flow, volume, and duration created by development projects be managed? This chapter describes the technical analyses that provided the basis for development of hydromodification control standards for the Santa Clara Basin.

4.2 DESIGN APPROACHES

Several approaches to the design of on-site measures for hydromodification control were explored:

- **Flow duration control** is a method that maintains the magnitude and duration of post-project flows at the same level as the pre-project flows, for the full distribution of flows between an upper and lower limit. The flow duration approach considers the entire multi-year discharge record, as opposed to a single event. Flow duration control also achieves volume control for the full distribution of flows.

- **Volume control** is an approach in which only the amount of runoff generated from the pre-project site may be discharged from the site after development. The difference between the pre-project and post-project runoff volumes is stored on-site in a basin and either infiltrated, discharged to another stream segment which would not be impacted by increased flows, or discharged at a very slow rate (i.e., less than the critical low flow for the stream). There is no control of the discharge rate or duration of the remaining (pre-project) runoff volume.

- **Hydrograph matching** is a method that maintains the post-project volume and distribution of flows at the same level as the pre-project flows for a single design storm event. This method is used in combination with a volume control basin to provide control of the discharge rate of the pre-project volume.

4.3 SUMMARY OF SUPPORTING TECHNICAL ANALYSES

In developing a proposed hydromodification control standard, a number of technical issues needed to be addressed:

1. What is the rainfall event, or range of events, below which the standard and management requirements apply (i.e., what is the design rainfall event)?
2. Will HMP controls be effective in protecting streams if they are designed based on discrete rainfall events or do they need to control increases in runoff based on a continuous flow record? For example, are volume control and/or hydrograph matching for discrete events an effective strategy? Are these approaches technically and economically feasible?
3. Is it possible to design an HMP control that matches the magnitude and duration of the pre-project runoff pattern (i.e., provide flow-duration control)? Is this approach technically and economically feasible and protective of the stream?

A series of technical memoranda were prepared to answer these questions. A summary of the findings and conclusions of Technical Memoranda (TMs) #4 through #8 is presented in Table 4-1 and described below[1]. These memoranda provided the technical basis and justification for the proposed hydromodification standard and performance criteria. The memoranda in their entirety are included in Appendix C of this report.

Range of Storms to Manage

Provision C.3.f.iv.3 of the permit requires that the HMP identify the maximum rainfall event below which the standard applies, or range of rainfall events for which the standard applies[2]. TM #4, *Evaluation of the Range of Storms for HMP Performance Criteria*, provides an evaluation of the range of flows that are the most important when considering stream channel erosion and hydromodification impacts. The evaluation is based on the erosion potential (Ep) methodology[3] developed for the Thompson Creek Subwatershed. It considers two land use scenarios, pre-urban (pre-1970) and future development in 2020, as an example of a "before" and "after" watershed condition, and assumes a stable, healthy stream as a baseline condition.

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[1] TM #1 covers the HMP Assessment Methodology and TM #2 addresses the Exempt Areas Analysis, which is presented in Sections 2.8 and 5.3. TM #3 on Hydromodification Control Standards was incorporated into Chapter 5.

[2] RWQCB staff has indicated that, although paragraph C.3.f.iv.3 refers to rainfall events, management of hydromodification should be focused on runoff and stream flows (personal communication with Jan O'Hara, RWQCB). Appendix A of TM #4 provides a discussion of the distinction between rainfall event and flow event frequencies or return periods.

[3] The erosion potential (Ep) is a measure of amount work done hydraulically on the stream channel above a baseline condition (pre-project). Ep is expressed as a ratio of the post-project work done to the pre-project work done. Work done is measured using the "effective work index" (W) described in Chapter 3.

Table 4-1
SUMMARY OF HMP TECHNICAL MEMORANDA #4 - #8[4]

Topic	Preliminary Conclusions
Evaluation of Range of Storms	
a) TM #4 – Define the rainfall event below which these standards apply.	• Critical low flow, Qc (approx. 10% of 2-year pre-urban peak discharge) to the 10-year pre-urban peak discharge.
Volume Control / Discrete Events	
a) TM #5 – Volume control effectiveness	• Volume control alone does not protect stream from increased erosive forces.
b) TM #7 – Hydrograph matching	• Sizing flow control basins to match the pre-project runoff hydrographs for discrete events does not closely reproduce the pre-project flow-duration patterns for other storms.
c) TM #6 – Example problem (SCS)	• Basins are technically feasible and may be economically feasible for infiltration rates of 0.2 in/hr and greater. • From 7% to 10% of the contributing <u>impervious area</u> (public streets, in this example) is required for volume control facilities sized for the 2-, 5-, and 10-yr storms.
– Cost analysis	• Costs do not vary much for volume control basins designed to control the 2-, 5-, and 10-yr storms. • About $3-4K per lot for onsite BMP, plus $1-2K per lot for regional basin (excluding land costs); maximum basin depth of 4.0 feet.
Flow Duration Control	
a) TM #7 – Basin sizing for flow-duration matching	• Basin and outlet structure can be sized to match pre-project flow-duration curve
b) TM #7 – Example problem (Thompson Creek)	• About 3-5% of the drainage area (4-6% of impervious area) is required for flow duration control (Infiltration rate = 0.2 in/hr); basin depths range from 10 feet for 3% to 4 feet for 5%.
– Cost analysis	• About $600 per lot for regional basin (excluding land costs).
c) TM #8 – Small project example in San Jose (3.6 acre, 12-lot subdivision)	• Basin sized using HEC-HMS model, SCS, and Rational Method; HMS model result was smallest. • About 1-2% of drainage area (3-5% of impervious area) required for flow duration control basin (infiltration = 0.2 in/hr), moderately steep slopes; basin depth of 1.75 to 3.0 feet; landscape controls on individual lots reduced basin size by about 35%.

[4] TM #1 covers the HMP Assessment Methodology and TM #2 addressed the Exempt Areas Analysis, which is presented in Section 2.8 and 5.3. TM #3 on Hydromodification Control Standards was incorporated into Chapter 5.

The analysis looks at cumulative “work” curves for various stream cross-sections before and after development. “Work” is a measure of the erosive hydraulic forces on the stream, and a cumulative work curve shows the percentage of total amount of work done for various stream flow rates occurring over the period of rainfall record (as simulated by the hydrologic model). The cumulative work curves showing the range of significant flows at selected cross-sections before and after development are presented in Figures 4-1 and 4-2.

These figures show that the flows that appear most important in controlling erosion and sediment transport processes range from near zero to the 10-year peak flow. A significant amount of the total work done (90-95%) on the channel bed and banks is associated with flows up to the 10-year peak flow. Flows higher than the 10-year peak flow perform a very small percentage of the total work (5-10%) because they occur infrequently over the period of record. A comparison of Figure 4-2 to Figure 4-1 indicates that a larger percentage of work is done by the lower flows than what was done before development; however, the range of significant flows appears to be the same as Figure 4-1. Selecting the 10-year predevelopment peak flow as the upper limit is consistent with a “knee of the curve,” cost-effectiveness approach for controlling erosive flows.

A range of flows should be selected that is protective of all stream segments downstream of the discharge point. The 10-year peak flow is believed to be an appropriate upper limit for the range of flows to be managed in the Thompson Creek Subwatershed considering results at all cross-sections (and later assessments confirmed this to be true for the Ross Creek Subwatershed as well, as described in Chapter 3). There may be locations in the downstream portion of the watershed that could control a range of flows with an upper limit less than the 10-year peak flow and be protective of downstream segments; however, an Ep analysis would have to be performed consistent with the methodology described in this report to confirm this for a particular project.

The lower limit of the range of geomorphically significant flows is based on the critical flow in the stream, “Qc,” i.e., the flow that produces the critical shear stress and initiates bed movement. This concept was discussed in Chapter 3. Estimated critical flows for Thompson Creek ranged from 1 cfs to 18 cfs depending on the conditions of the stream segment. Critical flows for Ross Creek range from 15 cfs to 25 cfs, again depending on the location in the stream. As described in Chapter 3, the in-stream critical flow for each stream segment was related to the pre-urban 2-year peak flow for that segment. For both Thompson and Ross Creeks, the critical flow was roughly equal to 10% of the pre-urban 2-year peak flow.

In conclusion, the range of flows considered important for managing hydromodification is from Qc (10% of the pre-urban 2-year peak flow) to the pre-urban 10-year peak flow.

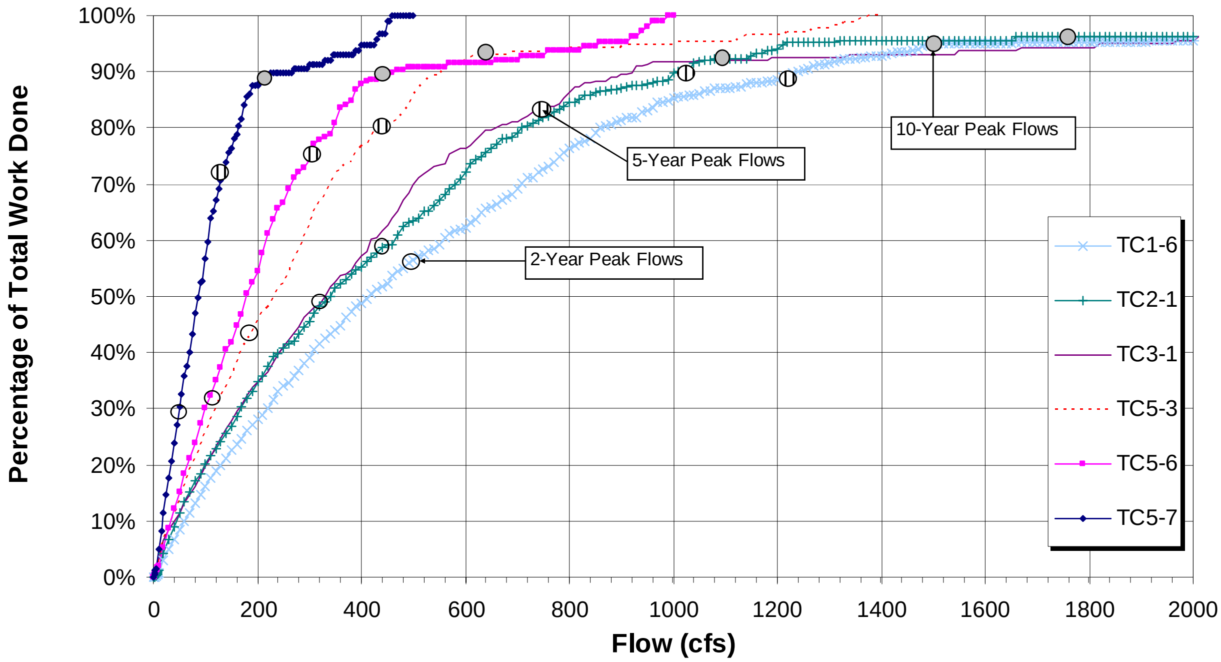

Figure 4-1 - Cumulative Work Curves Showing Range of Significant Flows <u>before</u> Development (using Thompson Creek stream segments as an example)

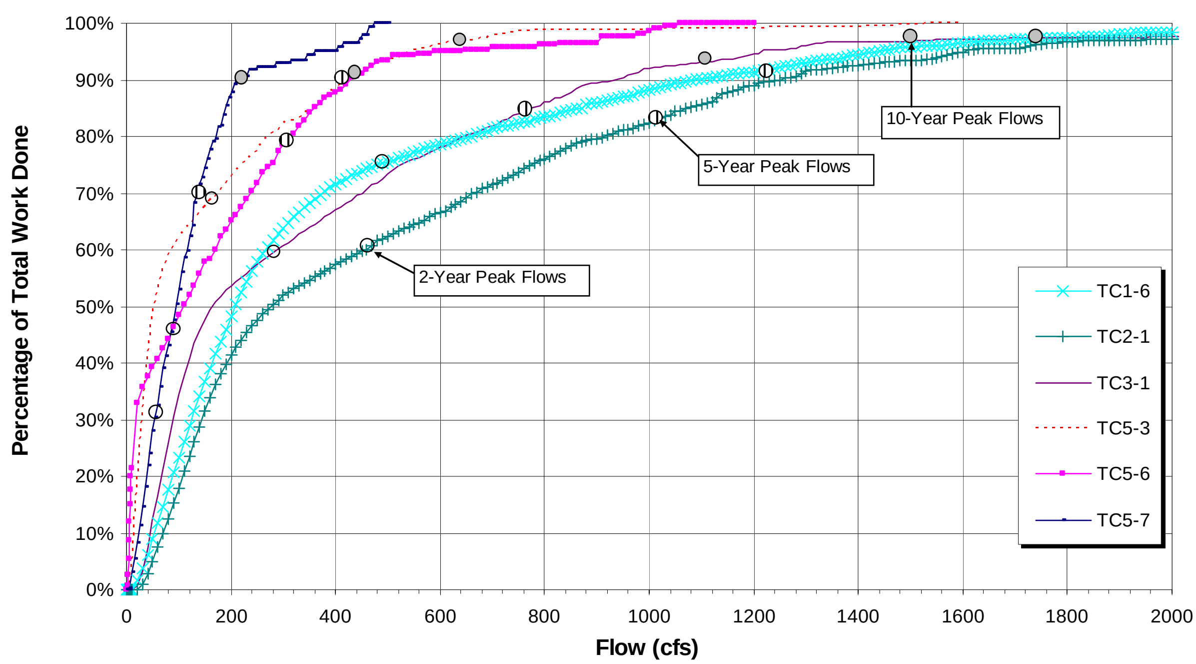

Figure 4-2 - Cumulative Work Curves Showing Range of Significant Flows <u>after</u> Development
Note: 2-, 5-, and 10-year peak flows indicated represent <u>pre-development</u> peak flows for comparison with Figure 4-1.

Flow Duration Control

Historically, stormwater management facilities have been designed to maintain peak flow rates at their pre-development levels to prevent increases in the frequency of flooding due to new development. Facilities that control peak flow rates usually allow the duration of flows to increase, which can cause increased erosion of the downstream system. Therefore, stream systems that require protection from hydromodification require BMPs that control the duration of geomorphically significant flows (flows capable of moving sediment). Peak flow controls alone are not adequate for erosion control. In Ontario, Canada, MacRae (1996) observed that attempts to control the 2-year discharge with no consideration for the duration of flows resulted in equally degraded streams as implementing no BMP at all. This fact has also been recognized in western Washington, where the Department of Ecology has adopted a flow duration control standard in which pre- and post-project flow duration curves must be matched according to specified criteria.

TM #7, *Flow Duration Control Example*, provides two examples of the design of flow duration controls, one for the Thompson Creek Subwatershed and one for a watershed in Southern California. The flow duration approach involves: 1) simulating the runoff from the project site, pre- and post-project, using a continuous rainfall record (50 years of record in this case); 2) generating flow-duration curves from the results; and 3) designing a flow control facility such that when the post-project time series of runoff is routed through the facility, the discharge pattern matches the pre-project flow-duration curve. An example of the flow duration curve for the Thompson Creek example, which illustrates the hours of flows higher than or equal to each flow rate from the continuous simulation, is presented in Figure 4-3. The objective is to size a control measure such that the post-project curve matches the pre-project curve over the range of significant flows.

The continuous runoff time series from the future development is routed through a detention basin that diverts and retains a certain portion of the runoff. This portion to be retained is essentially the increase in surface runoff volume created between a pre-project and post-project condition. This captured runoff is assumed to be infiltrated in the basin for this example but can also be disposed of via evapotranspiration and/or discharge at less than the critical flow of the stream (Qc) The allowable discharge from the basin for this detained volume is 10% of the pre-project 2-year peak flow from the project site (called “Qcp”) [5].

The flow duration basin is designed to have two pools: a low flow pool and a high flow pool. The low flow pool is designed to capture the difference in volume of runoff between the pre- and post-project conditions, as describe above. It will also capture small to moderate size storms, the initial portions of larger storms, and dry weather flows. The high flow pool is designed to store and release higher flows to maintain, to the extent possible, the pre-project runoff conditions. A flow duration basin can also serve as a water quality treatment facility and can be designed to treat dry and wet weather flows using a combination of extended detention and natural treatment processes.

[5] In computing Qcp, the allowable low flow discharge from a flow control structure on a project site, the original condition of the site before development must be considered. This does not imply that the developer is being required to provide flow controls to match pre-development conditions; rather, it is a means of apportioning the critical flow in a stream to individual projects that discharge to that stream, such that cumulative discharges do not exceed the critical flow in the stream. A description of the method for computing Qcp is provided in Appendix F.

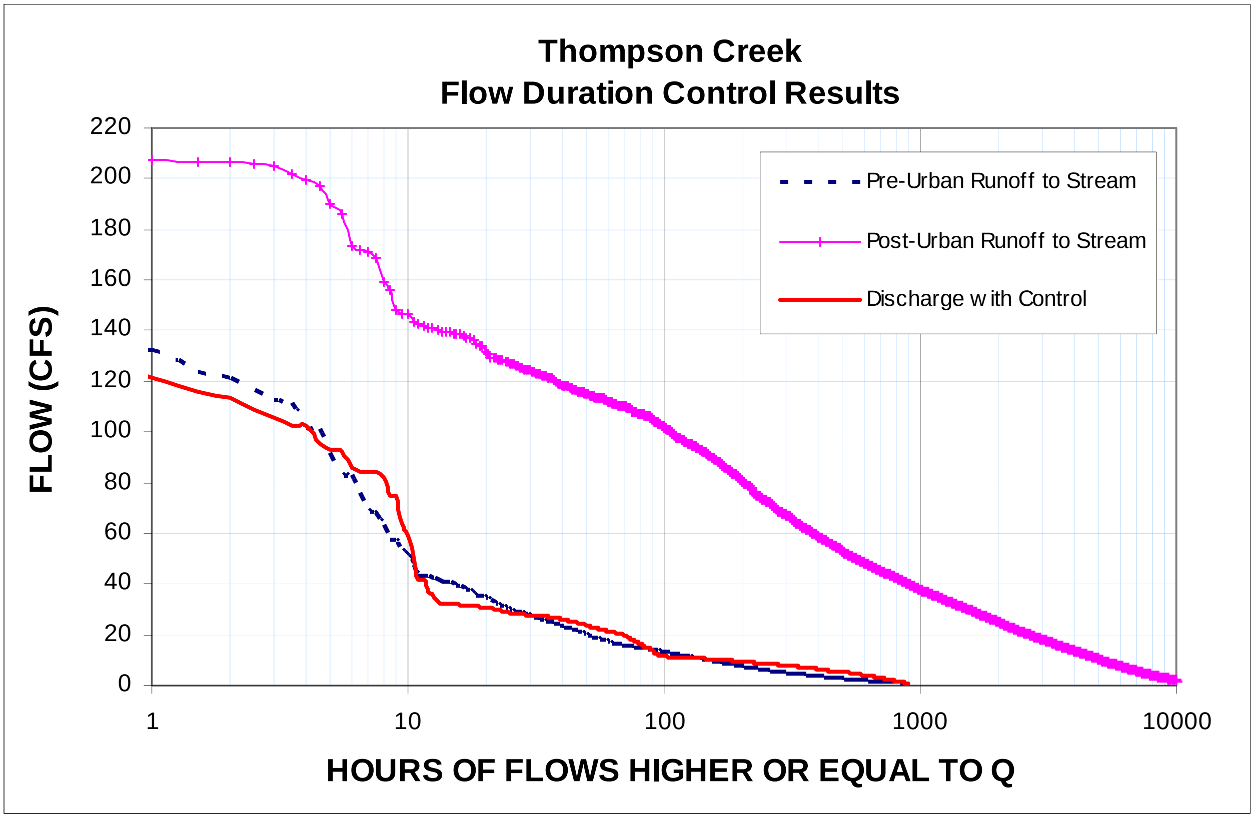

Figure 4-3 Flow Duration Curves for Thompson Creek Example

TM #8, *Sizing Flow Duration Controls for a Small Development Project in San Jose*, describes the application of the flow duration control analysis for a 12-lot, 3.6-acre subdivision in San Jose. In this example, about 1-2% of the drainage area was required for a flow duration control basin (given an infiltration rate of 0.2 in/hr, moderately steep slopes, and basin depths ranging from 1.75 to 3 feet). Hydrologic source controls (landscape features that reduced runoff) on individual lots reduced the basin size by about 35% in this example. (The effectiveness of site design and source control measures in achieving flow control and volume reduction depends on the imperviousness of the developed site.)

More details on these flow duration basin sizing examples, including cost estimates, are provided in Chapter 6. The economic feasibility of these controls is difficult to generalize, as it is highly dependent on site conditions; however, costs are similar to those required for traditional stormwater detention basins. Combining basins with treatment BMPs and using hydrologic source controls to reduce runoff can improve cost-effectiveness.

Basin design, specifically depth and area requirements, also affects feasibility. A shallow (1-3 foot) basin is more easily integrated into parks, playing fields, and other multi-purpose facilities; however, the surface area will be larger than a deeper basin. On the other hand, deeper basins (4 to 6 feet deep) will require less land area but will have less opportunity for alternate uses and may need fencing or other security measures.

Volume Control and Hydrograph Matching

Technical Memorandum (TM) #5, *Evaluation of Volume Control Effectiveness*, describes an analysis of the effectiveness of volume control methods for managing hydromodification. Volume control means that only the amount of runoff equal to that generated from the pre-project site may be discharged from the site after development. The difference between the pre-project and post-project runoff volumes is stored on-site in a basin and either infiltrated, discharged to another stream segment (within the same subwatershed) which would not be impacted by increased flows, or discharged at a very slow rate (i.e., Qcp). It was originally thought that a volume control structure would be easier to design with standard engineering methods than a flow-duration control structure and thus less costly for small developments to comply with HMP requirements.

However, for control measures designed to maintain the pre-project runoff volume, it is assumed that there is no control of the discharge rate. When development increases the amount of impervious surface on a site, the pre-project volume is discharged at a higher flow rate and has a higher erosive power than the pre-project runoff. The evaluation found that volume control does not account for these differences in erosive power for the same volume at higher flow rates. To evaluate the effect of hydrograph shape[6] while maintaining pre-project volume, the work done by several hydrographs having different shapes but the same volume was compared to the work done by the pre-project hydrograph. The conclusion was that hydrograph shape does matter and unexpected stream erosion is likely if managing volume alone. (Refer to TM #5 in Appendix C for more details.)

From this result, hydrograph matching was then tested. TM #7, *Flow Duration Control Example*, provides a discussion of the effectiveness of hydrograph matching. Hydrograph matching is a method that maintains the post-project volume and distribution of flows at the same level as the pre-project flows for a single design storm event. This method is used in combination with a volume control basin to provide control of the discharge rate of the pre-project volume (i.e., after the difference between pre- and post-project runoff volume is removed, the remaining volume is discharged at a rate that matches the peak and duration of the design flow hydrograph.).

The analysis in TM #7 compares the effectiveness of various basins designed by matching discrete storm hydrographs at reproducing the pre-project flow duration curve. Specifically, three control basins were designed using independent discrete storm sizes (2-year, 10-year, and 50-year), and one sized using the full 50-year hourly record of runoff generated by the HEC-HMS hydrologic model.[7] The analysis shows that basins sized using discrete events do not match the pre-project flow duration curve (i.e., pre-project flow durations were exceeded over the range of expected flows). Use of a hydrograph matching approach for flow control basin design could result in stream channel erosion if widely used throughout a drainage area. Single event

[6] A hydrograph is a plot of stormwater flow versus time. The shape of the hydrograph describes the peak flow, volume, and duration of runoff for a single storm event.
[7] The Hydrologic Engineering Center Hydrologic Modeling System (HEC HMS) model is the model used to simulate the hydrology of the test watersheds to determine the stream flows resulting from a 50-year rainfall record under different land use scenarios (see Chapter 3, Section 3.3).

management strategies do not account for frequent low flows less than the 2-year storm, soil moisture conditions before a storm, partially filled basins when the following storm arrives, or the natural variability in rainfall patterns.

In conclusion, hydromodification controls designed for discrete event volume control or hydrograph matching do not provide adequate protection of the erosion potential of streams. The recommended method for hydromodification control is to maintain the pre-project flow duration curve via a flow duration control structure (supplemented by low impact development strategies that reduce the amount of post-project runoff generated at the site).