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MEMORANDUM

Date:	February 23, 2010
To:	Chris Fitzer (EDAW|AECOM)
From:	Chris Bowles, Ph.D. and Chris Campbell, M.S.
Project:	08-1033 – Alder Creek Watershed Management Action Plan
Subject:	Recommendations for future hydromodification analysis methods and tools, and potential mitigation actions.

BACKGROUND

cbec, inc. (cbec) has been requested by AECOM to provide recommendations for future hydromodification analysis methods and tools, and potential mitigation actions for the Alder Creek Watershed Management Action Plan (ACWMAP) (AECOM, 2010).

The Sacramento Stormwater Quality Partnership (SSQP) is currently in the process of developing a Hydromodification Management Plan (HMP) as part of their 2008 MS4 Permit requirements with the Central Valley Regional Water Quality Control Board (RWQCB). The tentative schedule for completion of the HMP is mid 2011. However, in the period prior to the HMP being finalized, the SSQP are developing Interim Hydromodification Criteria (IHC) which will provide the local jurisdictions, development community and other applicants with criteria to use in the interim, prior to finalization of the HMP, to evaluate and mitigate for hydromodification impacts for individual projects. The IHC have not currently been finalized but it is anticipated that a possible format for the IHC is as follows. **The information provided here is for preliminary guidance only, is provided in terms of cbec's professional advice and the current direction of the SSQP, but has not been adopted by the SSQP.**

INTERIM HYDROMODIFICATION CRITERIA

Introduction

Interim Hydromodification Criteria (IHC) are intended to provide interim guidance to applicants on the methodologies required to minimize development-related changes in stormwater runoff from causing, or further accelerating, stream channel erosion, degradation, or other adverse impacts to beneficial stream uses, prior to completion of full and detailed guidance, which will be provided by the Final Hydromodification Management Plan (HMP) being produced by the SSQP. It is anticipated that IHC will be available, according to the current schedule, by approximately early 2011. The following provides suggested interim guidance for the local jurisdictions and development community within the Alder Creek Watershed, HMP background, analysis tools criteria and mitigation options.

Background on Hydromodification Regulations

Over recent years a number of existing and proposed National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) Permits have included hydromodification control requirements as a component of new development permit requirements. The first MS4 permits which required a Hydromodification Management Plan (HMP) were issued for the San Francisco Bay Area from 2001 to 2003 and are now covered under the Municipal Regional Permit (MRP) NPDES Permit, adopted in October 2009 (Order R2-2009-0074; NPDES Permit No. CAS612008).

Hydromodification and its impacts to receiving waters is best summarized by the Fact Sheet developed by the Office of Environmental Health Hazard Assessment. Further details are contained in the attachment.

Applicability Criteria

Applicability guidance on specific criteria where HMP regulations will apply are currently being developed by the SSQP. However, outlines for certain exemptions are provided in the SSQP's NPDES MS4 Permit (2008):

15 c (ii) This requirement[1] *does not apply to new developments and redevelopment projects where the project discharges storm water runoff into creeks or storm drains where the potential for erosion, or other impacts to beneficial uses, is minimal. The HMP shall describe the criteria used in determining the site-specific conditions applied to this requirement. Such situations may include, but not limited to the following:*

- *(a) Discharges into creeks that are concrete-lined or significantly armored;*
- *(b) Underground storm drain systems discharging directly to the rivers;*
- *(c) Construction of infill projects in highly developed watersheds, where the potential for single-project and/or cumulative impacts is minimal; and*
- *(d) Projects that do not create an increase in impervious surfaces over pre-project conditions.*

It is unlikely that channels such as Alder Creek will be exempt from HMP regulations based on the anticipated exemption criteria that are currently being developed.

Applicability mapping will be provided by the SSQP as an initial screening tool for the applicability of HMP regulations. The applicability mapping will show such items as existing channel typing.

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[1] 15 c (i) *HMP shall require controls to manage the increases in the magnitude (e.g., flow control), frequency, volume and duration of runoff from development projects in order to protect receiving waters from increased potential for erosion and other adverse impacts with consideration towards maintaining (or reproducing) the pre-development hydrology.*

Interim Hydromodification Criteria

As part of the HMP, the SSQP will develop acreage thresholds at which HMP regulations will be applicable. The threshold is not determined at this point, however, it is unlikely that this threshold will exempt projects within the Alder Creek Watershed.

Hydromodification Impact and Mitigation Assessment

It is likely that all projects within the Alder Creek Watershed will not be exempted from an HMP, and therefore, under IHC, will have to prepare and implement a Hydromodification Impact and Mitigation Assessment (HIMA), or similar, that demonstrates that post-development mitigated conditions have been designed so that the duration of sediment transporting flows in receiving waters is not altered as a result of development. The HIMA will likely include the following elements:

- Existing conditions geomorphic assessment
- Flow duration control matching for developments up to 500 acres using simplified flow duration control modeling
- Flow duration control matching for developments over 500 acres using continuous simulation flow duration control modeling
- Corresponding sediment transport work curves to assess the impacts of hydromodification and the mitigation measures on the geomorphology of the receiving waters.
- Hydromodification mitigation approaches to achieve flow duration control matching such that pre-project flow durations, peaks and volumes do not exceed post-project conditions.

It is possible that the final HMP will deviate significantly from the approach adopted in the IHC. Current developments State-wide, and the results of a pilot HMP project conducted in Sacramento County in 2009 (cbec, 2009), indicate that a risk-based, stream susceptibility approach may be adopted for the final HMP.

Further details of the elements of the HIMA under the IHC are as follows:

Existing conditions geomorphic assessment should be conducted. The purpose of this assessment is to quantify the existing susceptibility of the channel. The report produced recently for the Alder Creek Watershed Plan (AECOM, 2010) by nhc (nhc, 2009) provides a preliminary assessment on a watershed scale of Alder Creek, and some of the elements recommended here have been collected. However, on a project-by-project basis we recommend the following essential elements of a geomorphic assessment, developed from a modified and adapted version of a methodology being produced by Colorado State University and Southern California Coastal Water Research Project (Colorado State University, 2009) for the San Diego HMP (certain sections from the relevant report are quoted here):

- Integrated field and office/desktop components – *some of these elements have been completed by the ACWMAP and nhc.*
- Separate ratings for channel susceptibility in vertical and lateral dimensions – *the ACWMAP and nhc study has qualitatively described potential vertical and lateral susceptibility but has not used a system as recommended here*.
- Literature review of previous relevant studies in the watershed – *the ACWMAP provides a bibliography of relevant studies. Copies of all these studies and relevant background data are available upon request from the City of Folsom.*
- Summarize overall setting (using Google Earth or equivalent aerials):
    - Geologic setting, basin type, valley context, and tributaries – *these have been summarized by the ACWMAP.*
    - Recent watershed history (e.g. urbanization and fire) – *these have been summarized by the ACWMAP.*
    - Obvious grade control locations, human influences, and existing infrastructure – *these have been summarized by the ACWMAP*
- GIS analysis using the following metrics:
    - Contributing drainage area – *this has been calculated in the ACWMAP for the whole watershed, but not on a project by project basis.*
    - Topography, specifically valley slope in the region of the project – *these existing data are available from the City of Folsom.*
    - Precipitation, mean annual area-averaged precipitation – *the best available local precipitation data is available from the California Data Exchange Center (CDEC) (http://cdec.water.ca.gov/cgi-progs/staMeta?station_id=PRC) for the Prairie City Gauge, and has recorded hourly, daily and monthly precipitation data since it was installed in March 1985.*
    - Geomorphic confinement, valley bottom widths in the region of the project – *as part of the nhc study for the ACWMAP this is described qualitatively only.*
- Analysis Domain, whereby the effects of hydromodification may propogate for significant distances downstream and sometimes upstream from a region of impact. Typically, an analysis domain will be specified based on various criteria. However, in the case of the Alder Creek watershed, it is suggested that the Natomas Company Dam represents a substantial grade control and therefore may represent a downstream extent of analysis domain for the area of disturbance upstream of the dam. Downstream of the dam it is recommended that the analysis domain should extend from the area of disturbance downstream to the Caltrans culverts at the outfall of Alder Pond. *The analysis domain is not specifically covered by the nhc study and therefore the above is recommended.*
- Field screening, to assess vertical and lateral stability. Various methods are currently available to determine this, and the SSQP are developing appropriate tools to assist. However, methodologies should consider the following:
    - Vertical stability should consider channel bed conditions, such as Mobile (sand-dominated, low resistance), Transitional/Intermediate Bed (gravels/cobbles, intermediate resistance) Threshold Bed (coarse/armored bed, highly resistant substrate (hardpan)).

  - The three primary risk factors affecting vertical stability are armoring potential, grade control, and proximity to regionally-calibrated incision/braiding threshold.
  - Lateral stability should consider mass wasting or fluvial erosion/braiding, poorly consolidated or unconsolidated with fine/non-resistant toe material, poorly consolidated or unconsolidated with coarse/resistant toe material, consolidated, fully armored bedrock.
  - The three primary risk factors affecting lateral stability are Valley Width Index (VWI) (a measure of valley bottom width versus reference channel width (calculated in the office), proximity to a regionally-calibrated bank stability threshold, and the vertical susceptibility rating.

The nhc study conducted as part of the ACWMAP considered some of these elements quantitatively. However, for specific projects being undertaken in the Alder Creek watershed, additional investigations should be considered using the methodology developed by SCCWRP and Colorado State.

Flow duration matching for projects up to 500 acres – Under the IHC, it is likely that applicants will have to demonstrate that pre-project flow duration, peaks and volumes will match post-project conditions. Ideally, all projects should use continuous simulation modeling under IHC in order to calculate flow duration hydrologic statistics to inform HMP and design. However, building and using continuous simulation hydrologic models is extremely complicated, difficult, and hence costly. The IHC may allow for a simplified methodology to analyze these impacts for smaller developments, such as those less than 500 acres. cbec has developed a methodology to develop a long-term flow duration approximation from event-based hydrology models, otherwise known as the Simplified Flow Duration Calculation Methodology (SFDCM). This methodology is an improved and augmented version of that used by Northwest Hydraulics Consultants (nhc) for the Alder Creek Watershed Action Management Plan. The SFDCM uses event-based hydrology derived from SacCalc (Sacramento County's hydrology model), whereas the nhc method used for the Alder Creek watershed does not. Through recent research, cbec has concluded that the SFDCM, when used correctly, can provide a reasonable approximation for flow duration hydrologic statistics in lieu of full continuous simulation modeling. cbec compared the hydrologic results generated using the SFDCM to results generated for the same existing and project watershed conditions, and found that for most of the flow range the results compared closely. However, for baseflows and flows significantly less than approximately the 2-year return period events, the SFDCM did not compare so favorably. Therefore, cbec recommended that the SFDCM should not be used for the larger developments where use of continuous simulation may be more appropriate. In addition, available funds for larger developments are more likely to be able to accommodate the costs of continuous simulation modeling. Details of the SFDCM are given as follows.

Flow duration curves can be approximated satisfactorily using event-based model output (e.g. SacCalc) as a surrogate to using continuous simulation model output (e.g. HEC-HMS, HSPF, SWMM). Flow duration curves for existing and project conditions are often compared to determine how the flow regime will change under project conditions and if that change will alter the physical channel forming processes. Flow duration curves have typically been generated from continuous simulation model output, but the difficulty, time and cost to generate continuous simulation models can be prohibitive.

Some of the advantages of using event-based models over continuous simulation models include:

1. Event-based models like SacCalc are typically required of drainage studies, so unlike continuous simulation models, event-based models are readily available, from which the output can be manipulated using the approximation described here to perform flow duration analyses.
2. Continuous simulation models require a much more significant level of effort compared to event-based models considering the time required for model development, simulation, and post-processing.

The following process was used to generate flow duration curves from event-based SacCalc models using a recent local development as an example:

1. Use SacCalc to generate a series of n-year flood hydrographs (e.g. 2-, 5-, 10-, 25-, 50-, 100-year) for a 10-day storm duration[2].
2. Determine how many times each n-year flood should occur within a 100-year period[3] (e.g., fifty (50) 2-year floods).
3. Process the SacCalc hydrograph output (in its entirety) by placing the flows into flow bins (e.g. 50 to 60 cfs) of an appropriate discretization (based on watershed size).
4. Account for winter baseflows and summertime low flows to augment the SacCalc hydrograph output by putting all time not accounted for in the SacCalc output into the first flow bin[4].
5. Calculate percent time exceedence and plot.

To validate the event-based method, the event-based flow duration curves were compared to similar curves generated from continuous simulation model outputs prepared for the local development[5]. Figures 1 and 2 show flow duration curves derived from continuous simulation using HEC-HMS (HMS) and event-based models using SacCalc (SC) for existing (EX) and project (PRJ) conditions for two (2) compliance points (CP) in the local development. While the flow duration curves between SC and HMS are similar (but different) for discharges greater than 10% of the 2-year peak discharge (Q2[6]), they significantly differ for flows less than 10% of Q2. However, these significant differences below 10% of Q2 are considered inconsequential because they are the flows that do little to no work or sediment transport.

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[2] The 24-hour and 5-day durations were evaluated, but proved to generate insufficient runoff data to validate the method.

[3] For this analysis, a 49-year period was used to be consistent with the long-term continuous simulation modeling.

[4] For this analysis, regional data or synthetically derived baseflows were not used or generated because they were not required to validate the method.

[5] The long-term HMS models for hydromodification planning were derived from the event-based SacCalc models developed for storm drainage planning, and as such, are considered to provide a consistent base for comparison.

[6] Sediment transport processes are often cited to initiate with a lower bound of 10% to 25% of the 2-year peak discharge (Q2). Flows below this level theoretically move very little sediment, and hence, do very little work.

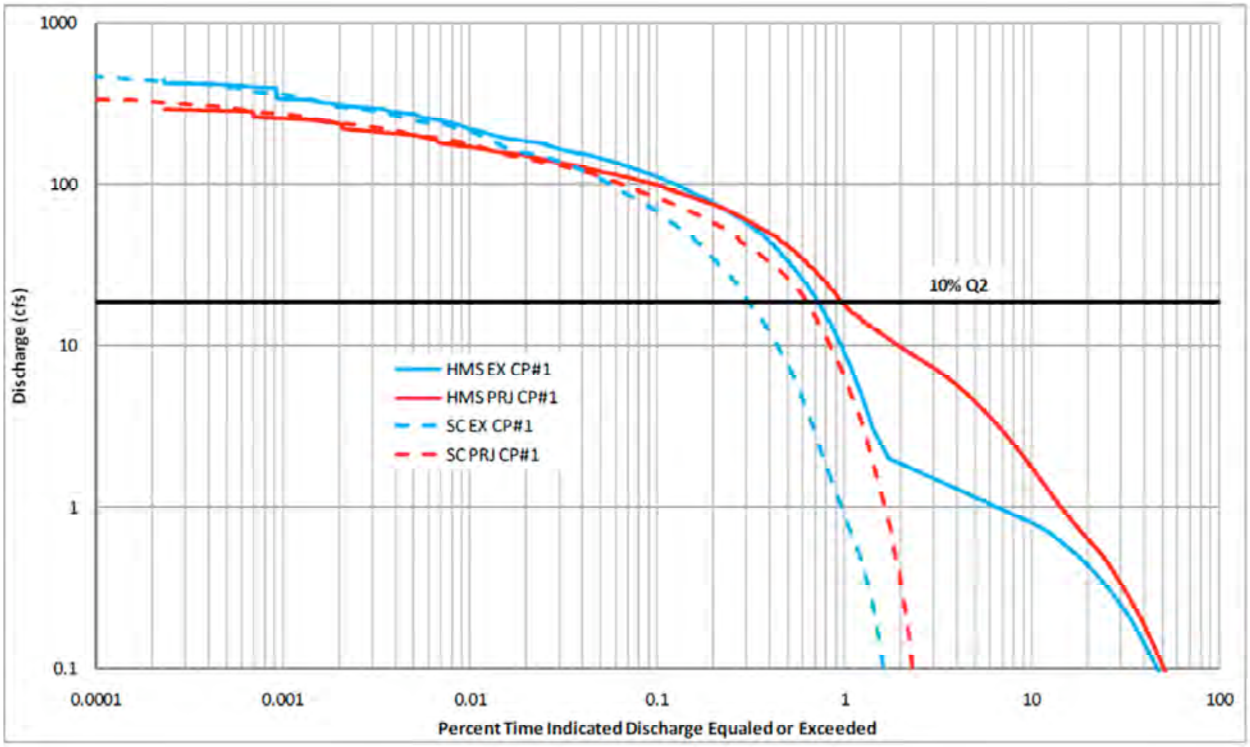

Figure 1 – Flow duration curve at compliance point #1

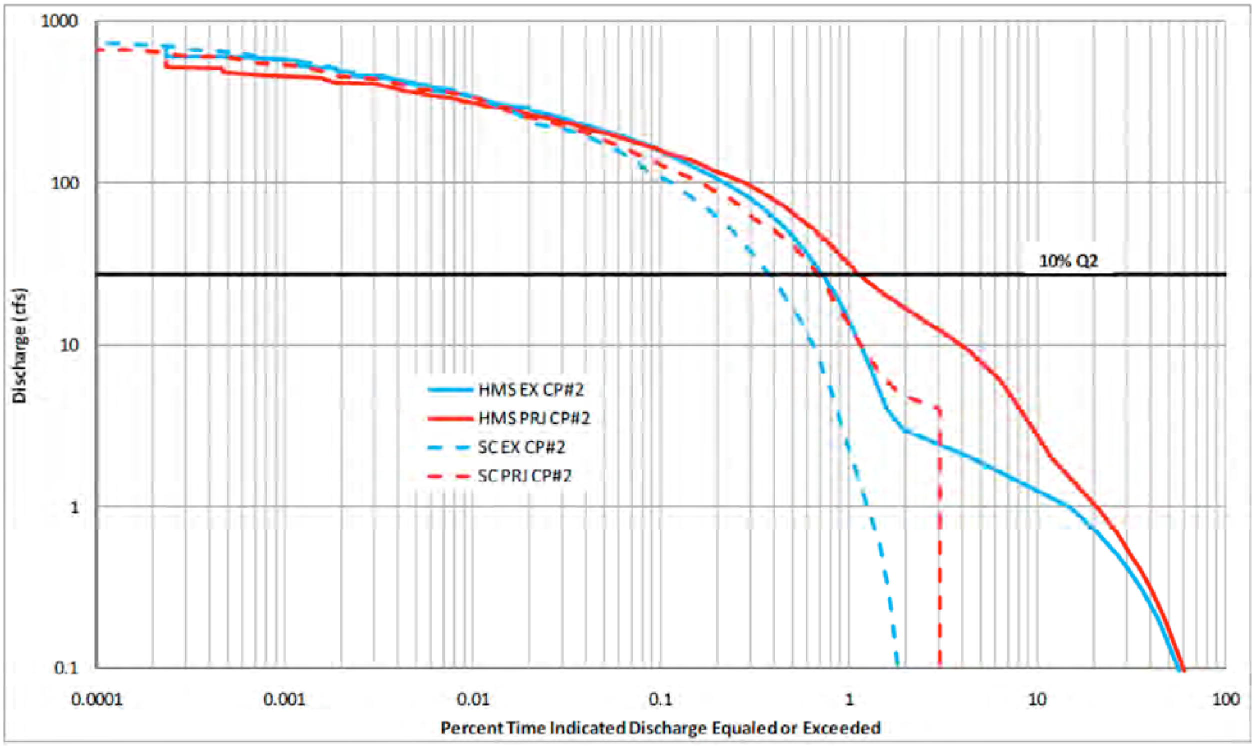

Figure 2 – Flow duration curve at compliance point #2

Figures 1 and 2 were then transformed into Figures 3 and 4 to compare the relative differences between long-term (HMS) existing (EX) and project (PRJ) conditions to the relative differences between event-based (SC) existing (EX) and project (PRJ) conditions. For flows greater than 10% of Q2 up through Q10, the relative differences between the pairs of model outputs are very similar, and as such, are portraying similar findings for geomorphically significant flows in the range of 10% Q2 through Q10[7].

Based on this analysis, it was shown that flow duration analyses can be derived from event-based models in lieu of continuous simulation modeling (as described above). Therefore, we believe this simplified method can be used to derive representative flow duration characteristics. As part of the HMP criteria, it is our recommendation that this simplified method be used for flow duration analyses for developments up to 500 acres.

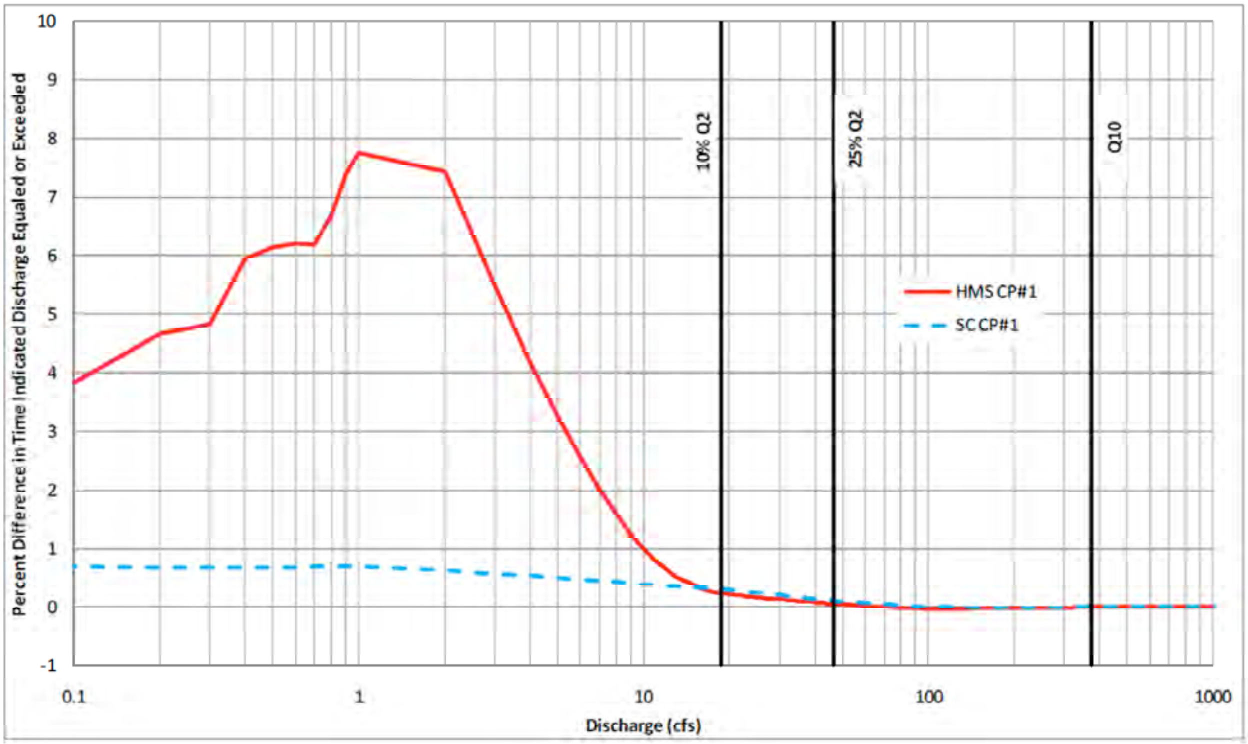

Figure 3 - Relative differences between continuous simulation (HMS; red) and the event-based methodology (SC; blue) at Compliance Point (CP) #1 (Q2 is 2-year peak discharge).

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[7] Peak flow values were based on 24-hour duration events to be consistent with what is normally cited.

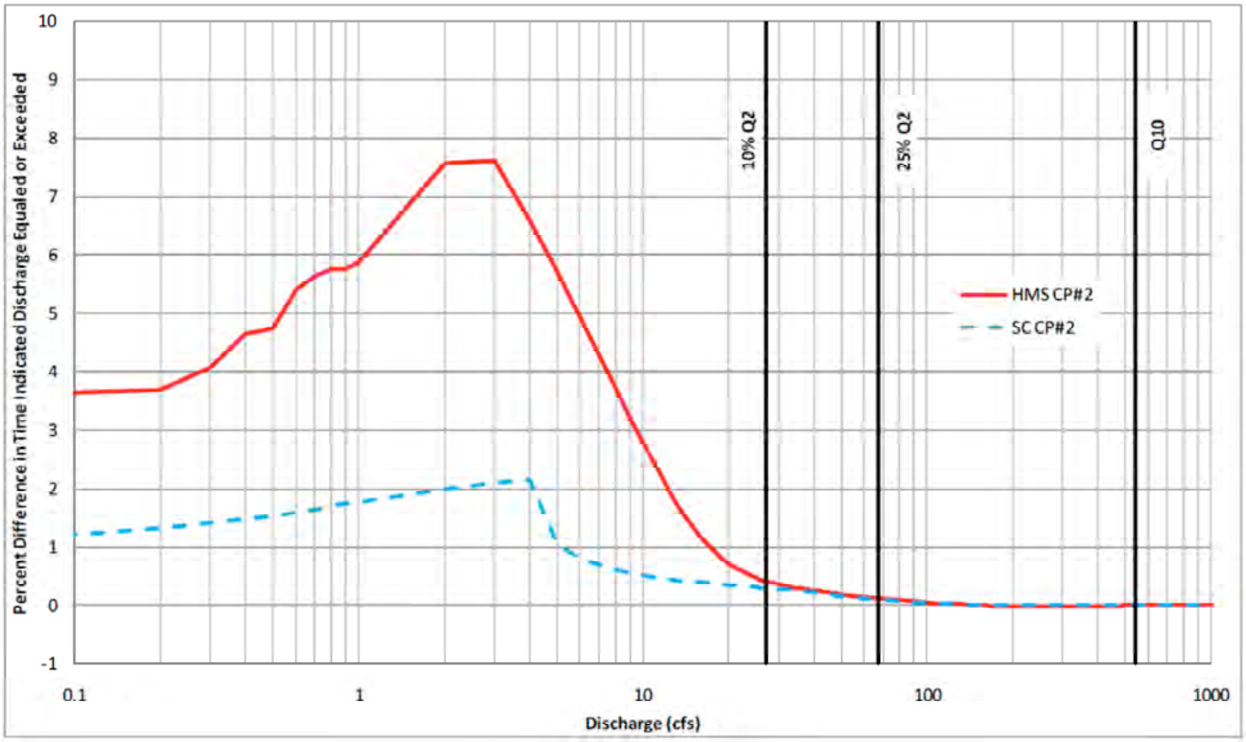


Figure 4 – Relative differences between continuous simulation (HMS; red) and event-based methodology (SC; red) at Compliance Point (CP) #2.

Flow duration matching for projects over 500 acres using Continuous Simulation Modeling. Guidance on undertaking continuous simulation modeling to size storm water facilities is provided as follows, with the following sections quoted from a memorandum written by Brown & Caldwell (Brown & Caldwell, 2008) and referenced through the San Diego HMP (Brown & Caldwell, 2009).

Continuous simulation hydrologic modeling is frequently used to adequately size storm water control facilities. This is a significant break with the practice described in most local public agency hydrology manuals where event-based modeling is usually used to determine whether a storm water pond, swale or other device was properly sized. Event-based modeling computes storm water runoff rates and volumes generated by a synthetic rainfall event with a total depth that matches local records (e.g., rainfall depths shown in County isopluvial maps). By contrast, continuous modeling uses a long time series of actual recorded precipitation data as input a hydrologic model. The model in turn simulates hydrologic fluxes (e.g., surface runoff, groundwater recharge, evapotranspiration) for each model time step.

Continuous hydrologic models are usually run using one-hour or 15-minute time steps, depending on the type of precipitation data available and computational complexity of the model. Continuous models generate outputs for each model time step and most software packages allow the user to output a variety of different hydrologic flux terms. For example, a continuous simulation model setup with 25 years of hourly precipitation data will generate 25 years of hourly runoff estimates, which corresponds to runoff estimates for each of the 219,000 time steps (each date and hour) of the 25 year simulation period. While creating and running continuous simulation models involves more effort than running event-based models, the clear benefit of the continuous approach is that these models allow an engineer to estimate how often and for how long flows will exceed a particular threshold. Limiting how often and for how long geomorphically significant flows occur is at the heart of San Diego County's approach to hydrograph modification management.

Two common models are used for continuous simulation modeling, HSPF and HEC-HMS. HSPF refers to the Hydrologic Simulation Program-FORTRAN and is distributed by the USEPA. HECHMS refers to the Hydrologic Modeling System (HMS) produced by the US Army Corps of Engineers Hydraulic Engineering Center (HEC). Engineers unfamiliar with these software packages should seek out training opportunities and online guidance. The USEPA conducts training workshops around the US to help teach engineers how to use HSPF. HEC-HMS training is provided through ASCE and third-party vendors. The following list describes the major elements of developing a hydrologic model and using that model to size storm water facilities.

1. Select an appropriate historical precipitation dataset for the analysis.
    a. The precipitation station should be located near the project site or at least receive similar rainfall intensities and volumes as the project site.
    b. The station should also have a minimum of 25-years of data recorded at hourly intervals or more frequently.
2. Develop a model to represent the pre-project conditions, including
    a. Land cover types
    b. Soil characteristics
    c. General drainage direction and slope
3. Develop a model to represent the post-project conditions, including
    a. New land cover types – more impervious surfaces
    b. Soil characteristics
    c. Any modifications to the drainage layout
4. Examine the model results to determine how the proposed development affects storm water flows
    a. Compute peak flow recurrence statistics (described below)
    b. Compute flow duration series statistics (described below)
5. Iteratively size storm water control facilities until the post-project peak flows and durations meet the performance standard described below.

Understanding the Peak Flow and Flow Duration Performance Criteria

The HMP analyses are typically based on a peak flow and flow duration performance standard. To compute the peak flow and flow duration statistics described in the standard, model users must have a method for evaluating long time series outputs (usually longer than the 65,000 rows available in MS Excel 2003 and earlier versions) and computing both peak flow frequency statistics and flow duration statistics. We recommend computing peak flow frequency statistics by constructing a partial-duration series rather than an "annual maximum" series, because the partial-duration series provides better resolution for assigning recurrence intervals to events that occur more frequently than once per 10 years, which are the events that are most important for the HMP. This involves examining the entire runoff time series generated by the model, dividing the runoff time series into a set of discrete unrelated events, determining the peak flow for each event, ranking the peak flows for all events and then computing the recurrence interval or plotting position for each storm event. To limit the number of discrete events to a manageable number, we usually only select events that are larger than a 3-month recurrence when generating the partial duration series. We consider flow events to be “separate” when flow rates drop below a threshold value for a period of at least 24 hours. The threshold should be less than the two-tenths of the 5-year flow rate that forms the lower limit to the IHC control range, but high enough to create a manageable number of events in the partial-duration series – less than 200 events. For continuous modeling and peak flow frequency statistics, it is important to remember that events refer to flow events and not precipitation events. Peak flow frequency statistics estimate how often flow rates will exceed a given threshold. For example, the 5-year flow event represents the flow rate that is equaled or exceeded an average of once per 5 years (and the storm generating this flow does not necessarily correspond to the 5-year precipitation event).

Flow duration statistics are more straightforward to compute than peak flow frequency statistics. Flow duration statistics provide a simple summary of how often a particular flow rate is exceeded. To compute the flow duration series, rank the entire runoff time series output and divide the results into discrete bins. Then, compute how often the flow threshold dividing each bin is exceeded. For example, let’s assume the results of a 35-year continuous simulation hydrologic model with hourly time steps show that flows leaving a project site exceeded 5 cfs an average of about once per year for 30 hours at a time. This corresponds to a total of 1050 hours of flows exceeding 5 cfs over 35 years. Another way to express this information is to say a flow rate of 5 cfs is exceeded 0.34 percent of the time. Computing the “exceedance percentage” for other flow rates will fill out the flow duration series.

The intention of HMP performance standards is to limit the potential for new development to generate accelerated erosion of stream banks and stream bed material in the local watershed by matching the postproject hydrograph to the pre-project hydrograph for the range of flows that are likely to generate significant amounts of erosion within the creek. The geomorphically significant flow range has not officially been stated by the SSQP but it is probably reasonable to assume that analysis should extend from the 2-year flow to the 10-year flow (Q2 to Q10) under interim conditions. A suggested performance standard would require the following:

1. For flow rates from the pre-project 2-year runoff event (Q2) to the pre-project 10-year runoff event (Q10), the post-project discharge rates and durations shall not deviate above the pre-project rates and durations by more than 10% over more than 10% of the length of the flow duration curve.
2. For flow rates from Q2 to Q10, post-project peak flows may exceed pre-project flows by up to 10% for a 1-year frequency interval. For example, post-project flows could exceed pre-project flows by up to 10% for the interval from Q9 to Q10 or from Q5.5 to Q6.5, but not from Q8 to Q10.

Determining When a Storm Water Control Facility Meets the IHC Performance Standard

The previous section discussed how to calculate peak flow frequency and flow duration statistics. By comparing the peak flow frequency and flow duration series for pre-project and post-project conditions, an engineer can determine whether a stormwater control facility would perform adequately or if its size should be increased or decreased. The easiest way to determine if a particular storm water facility meets the IHC performance standard is to plot peak flow frequency curves and flow duration curves for the pre-project and post-project conditions.

Figure 5, following, shows a flow duration curve for a potential development. The three curves show what percentage of the time a range of flow rates are exceeded for three different conditions: pre-project, post project (baseline without detention) and post-project with storm water mitigation (baseline with detention). The increase in the duration of the geomorphically significant flow after development illustrates why duration control is closely linked to protecting creeks from accelerated erosion. Higher flows that last for longer durations provide the energy necessary to increase the amount of erosion in local creeks. The post-project mitigated condition would include stormwater controls designed to limit the duration of geomorphically significant flows. These typically take the form of modified storm detention basins, or flow duration control basins. Outlet structures are typically designed to release flows in a manner to mimic pre-project rates and durations. This means the stormwater control mitigations would counteract the effects of the increased pavement associated with development projects.

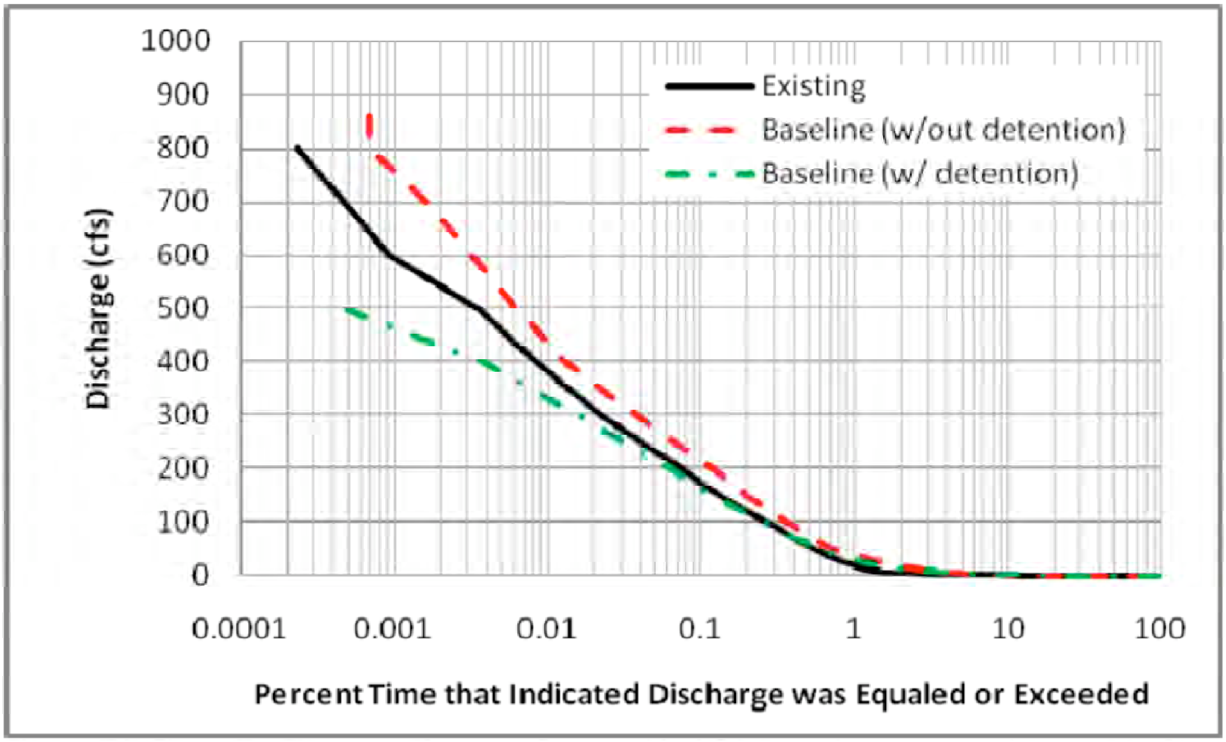


Figure 5 – Flow duration curve for a potential development with existing, project without flow duration control basins and project with flow duration control basins.

An example of a outlet flow control structure is shown by Figure 6.

Figure 6 - Flow duration control outlet structure. Notice different sized orifice located at varying elevations to mimic pre-project flow rates and duration. (Photograph taken by C. Bowles, Hitachi Redevelopment, City of San Jose, 2009).

In addition to flow duration analysis, it is recommended that a work analysis be conducted at representative channel cross sections throughout the project impacted reach. These are created in a similar manner to flow duration curves but are a function of the total work done per year in ft-lbf/ft^2. In this analysis, the resultant work curves, derived from the flow duration analysis, are checked to minimize erosive and degradational forces on the creek. Figure 7 shows that the post project total work has been matched to the pre-project total work at a particular point in the channel using flow duration control in stormwater facilities.

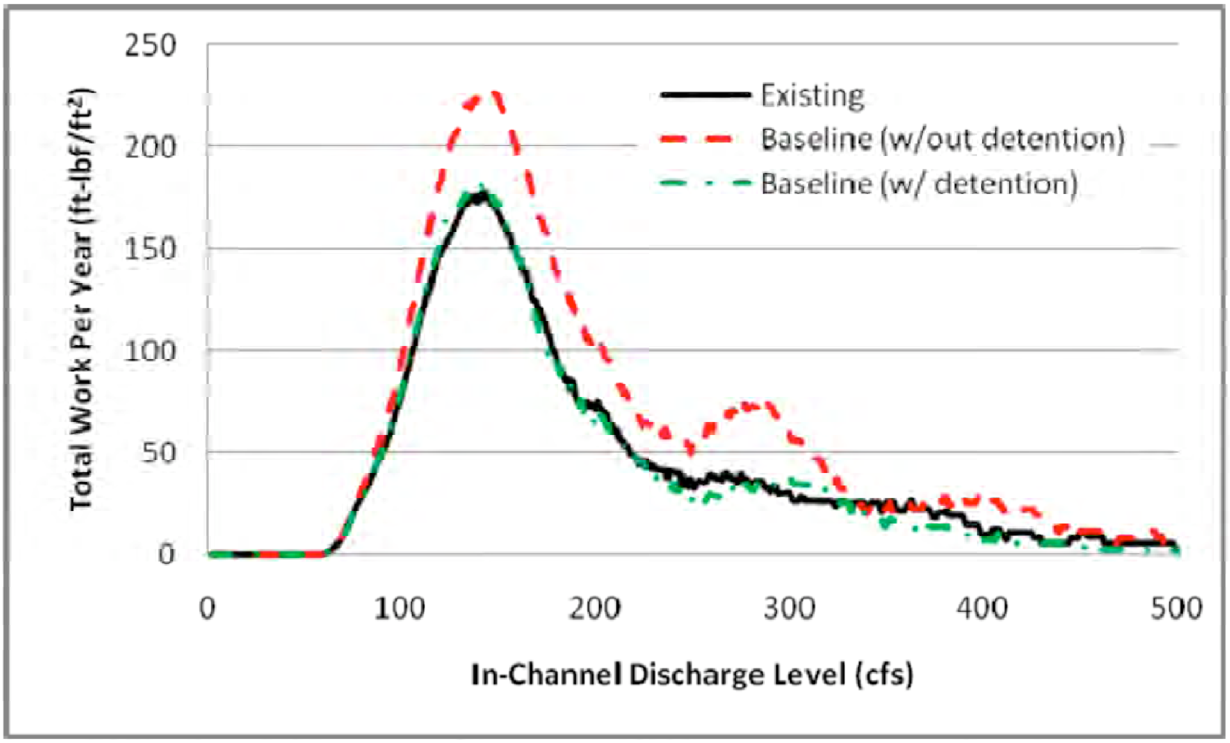


Figure 7 – Total work graph for existing, project without flow duration control basins and project with flow duration control basins.

HMP Mitigation Approaches

Based on the results of the HIMA described in the previous sections, HMP approaches will be required to mitigate for the impacts of development (through increase in impervious area) on receiving waters. Under the IHC, these mitigation approaches will have to be incorporated into the modeling and analysis techniques, described under the HIMA, to minimize impacts to the flow duration, peaks and volumes pre- and post-project.

In previous hydromodification studies undertaken Statewide, three typical approaches have been used to manage and mitigate the impacts of hydromodification. It is recommended that a combination of these approaches be used in future developments in the Alder Creek watershed. It is likely that these approaches will be recommended in the final HMP to mitigate for hydromodification. The SSQP are also developing tools that may be provided to applicants to assist with designing and sizing mitigation approaches. Further, guidance on these mitigation approaches is described in a fact sheet produced by the Office of Environmental Health and Hazard Assessment (OEHHA, 2009) (see Attachment) and summarized here as follows:

- Flow Control Approach - the use of modified extended detention basins (often called Flow Duration Control Basins or FDCs) or infiltration facilities (e.g. swales with underdrains) providing bioretention to control discharges into receiving waters in the geomorphic flow range responsible for most channel erosion. In other parts of Northern California, this flow range has extended between some fraction of the Q2 (2-year return period event) up to the Q10 (10-year return period event). Flows in this range are managed so that the pre- and post-development flow duration curves match within a defined tolerance.
- Landscape Approach – in which impervious areas drain to a series of highly pervious landscaping areas that act as dispersed infiltration facilities. These infiltration facilities are sized based on pre-determined ratios (typically around 5% of the developed area) and have been found to infiltrate the excess runoff within the range of erosive flows.
- In-stream Approach – the use of stream restoration approaches to stabilize and restore already heavily anthropogenically impacted receiving waters to better withstand the potential future impacts of hydromodification (reducing slope gradient by increasing sinuousity where geomorphically-appropriate or introducing step-pool drop structures, or conducting biotechnical bank stabilization, etc.)

References

- AECOM, 2010. Alder Creek Watershed Management Action Plan, Stakeholder Review Draft, January 11, 2010.
- Brown & Caldwell, 2008. Using Continuous Simulation to Size Storm Water Control Facilities, prepared as part of the San Diego Hydrograph Modification Plan, April 30, 2008. See also: http://www.projectcleanwater.org/html/wg_susmp.html
- Brown & Caldwell, 2009. Final Hydromodification Management Plan, prepared for the County of San Diego, California, December 29, 2009.
- cbec, 2009. Pilot Project to Assess Decision Support Tools for Hydromodification Management in the Sacramento Area, prepared for the Sacramento Stormwater Quality Partnership, March 2009, by cbec inc., eco engineering (http://www.sacramentostormwater.org/SSQP/development.asp).
- Colorado State University, 2009. Hydromodification Screening Tool for Southern California – Draft for Field Testing/TAC Review prepared for the County of San Diego, by Colorado State University (Bledsoe, Hawley) and Southern California Coastal Water Research Project (Stein), November, 2009.
- SSQP, 2009. Waste Discharge Requirements Order No. R5-2008-0142 Municipal Separate Storm Sewer System Sacramento and Associated Cities, Central Valley Regional Water Quality Control Board NPDES Permit for the Sacramento Stormwater Quality Partnership.

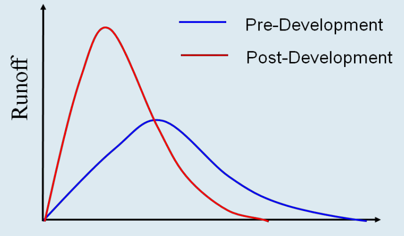
Attachments

- OEHHA, 2009. Hydromodification: Principles, Problems, and Solutions. Prepared by the Office of Environmental Health Hazard Assessment and the State Water Resources Control Board.

HYDROMODIFICATION

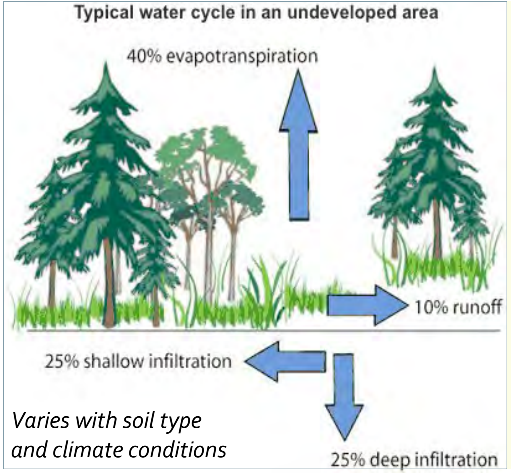
Principles, Problems, and Solutions

As watersheds urbanize, soil is compacted and covered with hardscape such as buildings and roads, known as **impervious cover**. This can cause an alteration of flow (**hydromodification**) that increases the volume of runoff and decreases the infiltration of rainwater, an important source of groundwater recharge. **Figure 1** shows stormwater discharges in an urban watershed (red line) and a pre-urban watershed (blue line). The greater volume and increased rate of flow that are associated with urbanization results in degradation of aquatic habitat and increased flood risk. This factsheet presents an overview of hydromodification and possible approaches to preventing and mitigating its effects.



J. Haltiner, PWA

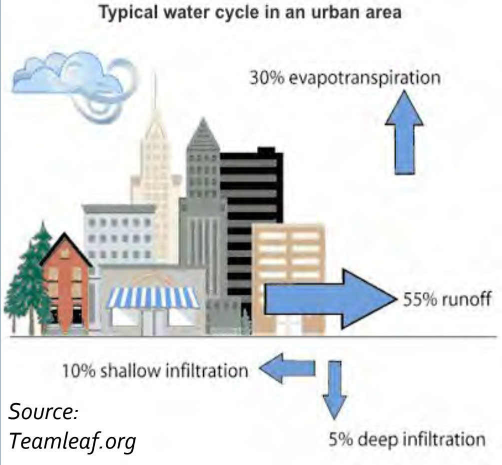
Effects of Hydromodification on the Water Cycle



Varies with soil type and climate conditions

Figure 2a (left): Water balance on undeveloped land. With natural cover, more rain and snowmelt infiltrates into the ground and less ends up as runoff.

Figure 2b (right): Water balance on developed land. As urbanization increases, less water infiltrates and runoff increases, up to 5-fold. There is a loss in the volume of groundwater recharge and reduced evapotranspiration (the uptake of water from plants and soils).



Source: Teamleaf.org

How Hydromodification Shifts the Water-Sediment Balance

Figure 3a

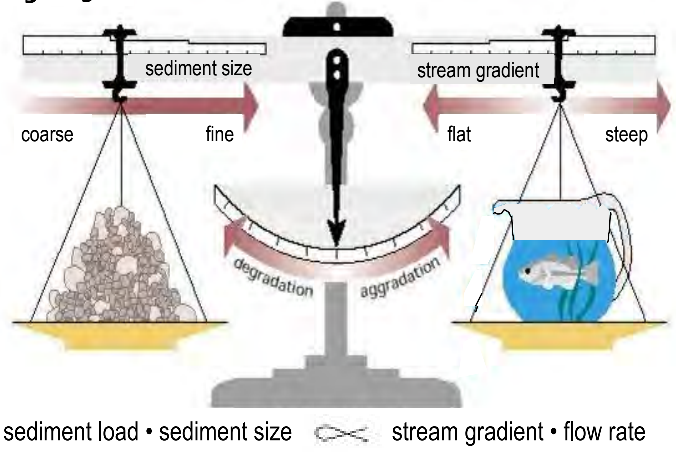
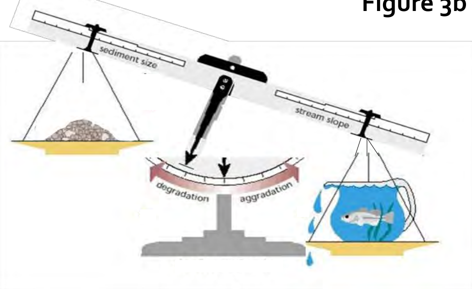


Figure 3b



Effects of hydromodification. The combination of reduced sediment supply and increased flow rate, associated with urbanization, causes degradation of the stream beds and bank.

Lane's diagram (**Figure 3a**) illustrates the relationship between the balance of water and sediment in a stream. Water naturally erodes and delivers sediment from the watershed into waterways. It is natural for some sediment to remain suspended in the water; the amount varies depending on watershed characteristics. Urbanization alters this balance by paving over sediment source areas and increasing runoff volume. The excess runoff volume and flow rate applies significant force to channel beds and banks, causing erosion and bed scour. This alters the balance of water and sediment in the stream, causing an increase in the stream gradient (slope from mountains to ocean), as shown in **Figure 3b**. This can result in habitat changes which can be detrimental to aquatic organisms and plants, frequently decreasing biodiversity. For example, salmon in California need cold, clear water and spawning gravel to reproduce. When spawning gravel is filled with fine sediment, fish eggs and hatchlings are smothered, adversely affecting salmon populations. There are a variety of solutions for reducing hydromodification and minimizing its impacts, described in the next section of this factsheet.

Solution #1: Low Impact Development (LID)

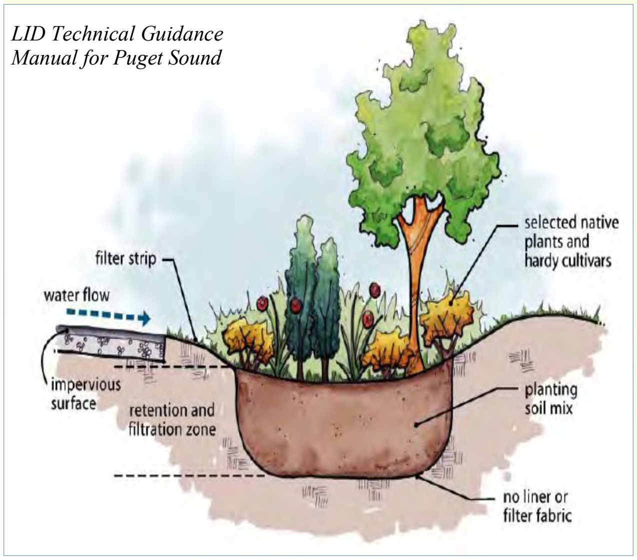
LID is an alternative method of land development that seeks to maintain and mimic the natural hydrologic processes by infiltrating, retaining, and slowly releasing stormwater on a site by site basis. LID often begins with careful site planning that considers the location of natural features and incorporates them into the stormwater management plan whenever possible. This may include retaining a wide riparian corridor to allow for natural stream processes, identifying and preserving areas with coarse sediment, protecting locations suitable for groundwater recharge, and considering soil permeability and slope when siting bioretention areas. This approach is generally known as **natural resource-based planning**. By taking advantage of nature's plumbing, infiltration capacity can be optimized.

LID is about source control: keeping water where it falls, rather than funneling it through pipes or channels that drain into local waterways. These techniques foster natural hydrologic processes and reduce the volume of runoff. Implementing these techniques can minimize the changes in the hydrological cycle that lead to erosion and degradation of aquatic habitat.

LID Applications

LID methods are especially cost effective in parking lots because pavement of one type or another makes up a significant percent of impervious areas in cities. **Interlocking concrete pavers** (left) allow water to infiltrate at the joints, while **pervious concrete or asphalt** (right) is made without sand, creating voids that promote infiltration.

Bioretention areas are small-scale facilities designed to promote infiltration/retention, and are incorporated into a site design most effectively when integrated with other LID techniques. A **rain garden** (below) is a planted depression that contains amended soil and drought-tolerant vegetation. Rain gardens are designed to handle most smaller storm events. If native soils are not amended and have a high percentage of clay, an underdrain or dry well could be placed under the garden to promote infiltration. Rain gardens can be used in a variety of commercial, residential and municipal settings (see right).



LID Technical Guidance Manual for Puget Sound

Curb cuts (right) permit water from parking lots and roads to enter the bioretention area where it is retained and infiltrated instead of ending up as runoff in a storm drain system. This helps to keep pollutants such as oil and heavy metals like copper and zinc (products of tire and brakepad wear) out of local waterways.

Solution #2: Instream Restoration Practices

Instream restoration practices (IRPs) modify the banks and beds of waterways using natural materials to return the stream to a less impacted condition and improves aquatic habitat. IRPs can affect two of the variables associated with hydromodification: the increased quantity of fine sediment (small particle size) and the increased slope (gradient) of streams and rivers (see Fig. 3b). IRPs contrast with conventional methods such as retaining walls and riprap, which damage aquatic habitat and often fail over time. All waterways are unique, constantly evolving, and change in response to urbanization, so it's important to use restoration techniques best suited to the condition of the particular waterway.

Solutions for Bank Erosion

Bank erosion is a natural process, but is accelerated by the effects of hydromodification, which can have multiple negative effects on the aquatic ecosystem and riparian habitat. Intense stormwater flows associated with compacted soil and impervious cover are a major contributor to bank erosion. The rate of erosion varies, depending on existing vegetation type and location, soil composition, and the frequency and intensity of flows. Multiple methods are available to address this problem, including **live stakes** (LS) and **brush mattresses**. LS (left) involves installation of live, woody cuttings into the bank that permits trees to grow and anchor the soil, and provides riparian habitat. Brush mattresses (right) are a thick mat of branches placed on the bank and held down with stakes. They provide a foundation that, over time, roots into and anchors the bank. A modification of LS are **joint plantings** (JP), which are live stakes that are pounded into the openings in riprap. These techniques are low in cost and complexity but reduce erosion and offer multiple ecological benefits.

Live stakes offer protection from shear stress and also allow the stream to adjust to change naturally.

Pictures: J. Turek, NOAA (left), Urban Creeks Council (right)

Brush mattress branches are laid perpendicular to water flow, then anchored with stakes and twine.

Solutions for Bed Scour

Channel bed scour refers to the erosion of the beds of streams and rivers. Like bank erosion, scour can be detrimental to the aquatic ecosystem, and varies depending on local geology (sand vs. less erodible clay and bedrock), sediment size, slope, and the rate of flow. One method to reduce scour is the installation of rock weirs, which span a stream in a variety of patterns. They function to reduce high flows and to maintain a low flow channel. Unlike a dam, rock weirs have depressions that permit the movement of sediment, which helps to maintain the water-sediment balance. A variation of rock weirs are step pools, which are a series of boulders constructed along a stream (see inset) to form pools that ultimately slow water flow, reduce scour, and reduce gradient changes, resulting in improved aquatic habitat. Another way to reduce bed scour is to remove undersized culverts, which increase erosive forces and inhibit fish from migration.

Step pool application along a stream. Riffles are produced from partly submerged boulders, where water moves rapidly. Riffles provide habitat for aquatic insects and spawning sites for many fish. Slow-moving, deep water is found in pools, where fish can find shelter.

Solution #3: Flow Duration Control Basins

Flow duration control (FDC) basins are another technique that effectively manage flow-related impacts caused by hydromodification**.** FDC basins are designed to capture and reduce the difference in pre- and post- development runoff volumes, in an effort to mimic pre-project flow conditions. They retain excess urban runoff, preventing erosive flows (flow rates that cause erosion). Stormwater initially fills in zone 'A', where it can infiltrate or be released at a non-erosive rate through small outlet pipes (**see Figure 4**). If the basin continues to fill, water will rise to zone 'B', where it may be discharged through a weir or evaporates. FDC basins differ from traditional detention/retention basins in that zone 'A' is larger to permit it to release water at slower, non-erosive flow rate. A limitation for all types of basins is that they trap sediment and can potentially contribute to the water-sediment imbalance.

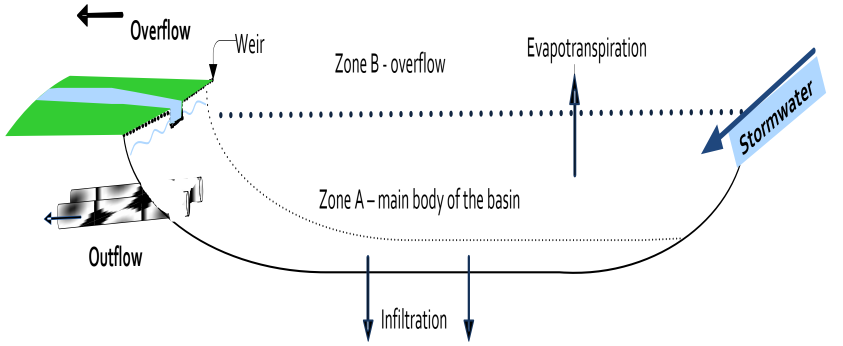


Figure 4

Figure 4. An FDC basin. Water enters the FDC basin and can exit via infiltration, evaporation, or discharge. If the water volume is smaller than the capacity of zone 'A', it can flow through small outlet pipes designed to release water at a non-erosive rate. If the volume is larger, it spills over the weir into a channel that moves water to the main waterway.

Source: Gary Palhegyi, Entrix

Conclusion

The techniques summarized in this factsheet provide measures to avoid, minimize, and mitigate the impacts of hydromodification. In the majority of cases, the best step is to consider the natural resources on and near the site, including the condition of local waterways. Hydromodification can often be reduced with thoughtful planning and the use of LID techniques. LID is usually the simplest approach to implement as well. If these changes can't be avoided, additional solutions can be used, including flow duration control basins and instream restoration. When new development occurs at sites near streams that have already been degraded, more emphasis on stream restoration should be considered. The following table summarizes one way to think of managing hydromodification:

Management Goal	Approach (listed by priority)
Avoid	Natural-resource based planning, source control (LID)
Minimize	LID, FDC basins, instream restoration
Mitigate / prevent further damage	Instream restoration, LID, FDC basins

More Information

The Low Impact Development Center	www.lowimpactdevelopment.org
Stormwater Manager's Resource Center	www.stormwatercenter.net
The Center for Watershed Protection	www.cwp.org
National NEMO Network	www.nemonet.uconn.edu
Sacramento County Rain Gardens	www.riverfriendly.org/raingardens
Federal Interagency Stream Corridor Restoration Manual	www.nrcs.usda.gov/technical/stream_restoration
Fluvial Geomorphology Training Module	www.fgmorph.com
Stormwater Program, SWRCB	www.waterboards.ca.gov/water_issues/programs/stormwater

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