FRAMEWORK FOR DEVELOPING HYDROMODIFICATION MONITORING PROGRAMS

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EXECUTIVE SUMMARY

In recognition of the pervasive effects of hydromodification (i.e. alteration of runoff patterns associated with change in land use that result in change in physical channel conditions) on southern California streams, many municipalities are now required to develop hydromodification management programs. Monitoring the effectiveness of these programs is critical because hydromodification management is in its infancy, and there is much to be learned from early efforts. This document is intended to provide a framework to assist state agencies, local jurisdictions, and municipal stormwater permittees in developing detailed hydromodification monitoring plans to address specific management and reporting needs.

Monitoring the effects of hydromodification is challenging. Physical changes associated with changes in runoff are difficult to assess because they can result from a combination of contemporary land-use changes, legacy land practices (e.g. grazing), and stochastic events (e.g. floods and fires). Furthermore, channel adjustments can occur dramatically and rapidly after extended periods of apparent stability and can vary over small distances. Separating out the effects of human activity from natural cycles of channel evolution further complicates hydromodification monitoring and requires much longer term monitoring than traditional water quality programs.

Given the need for long-term commitment and investment, we propose a tiered approach to hydromodification monitoring. This tiered approach can be implemented in phases with different elements being prioritized based on management information needs, condition of managed streams, and available resources. Monitoring for each element is based on one or more directed questions that guide specific monitoring designs:

Performance Assessment

1) How well do various BMPs, control strategies, and management measures perform relative to their design expectations and in light of how well they are maintained?
2) What factors influence the efficacy of hydromodification management strategies?

Effectiveness Assessment

3) How effective are specific management strategies at protecting the physical and biological integrity of streams from the effects of hydromodification (in the context of other watershed stressors)?
    a) How do these effects compare to patterns at unimpacted “reference” sites?
    b) Are the management strategies sufficiently protective of all stream types?
    c) How does effectiveness vary by stream type (e.g. substrate, planform, slope)?

Spatial and Temporal Trends Assessment

4) What is the spatial footprint of response to hydromodification effects or management actions relative to discharge locations?
    a) How far up or downstream do potential effects of hydromodification persist?

5) How do responses to hydromodification management vary over time?
    a) What is the effect of natural rainfall and runoff patterns on stream response in the presence or absence of management measures?
    b) How long do “restored” or “rehabilitated” stream reaches take to recover following remediation?
    c) How do responses vary based on stream type (e.g. substrate, planform, slope) and environmental setting (e.g. watershed position relative to upstream land use, floodplain condition)?

Ambient (Characterization) Monitoring

6) What is the physical and biological condition of streams relative to established regulatory or management objectives?
    a) How does condition vary by stream type (e.g. substrate, planform, slope) and environmental setting (e.g. watershed position relative to upstream land use, floodplain condition)?

In general, the first and second elements (performance and effectiveness monitoring) of hydromodification monitoring can be addressed by multi-year monitoring programs typically managed by municipalities and other local entities. In contrast, the third and fourth elements (trends and ambient condition) must be addressed over longer time scales (e.g., decadal) through cooperative regional monitoring that involves multiple entities including state, regional, local agencies and grant programs (Figure ES-1).

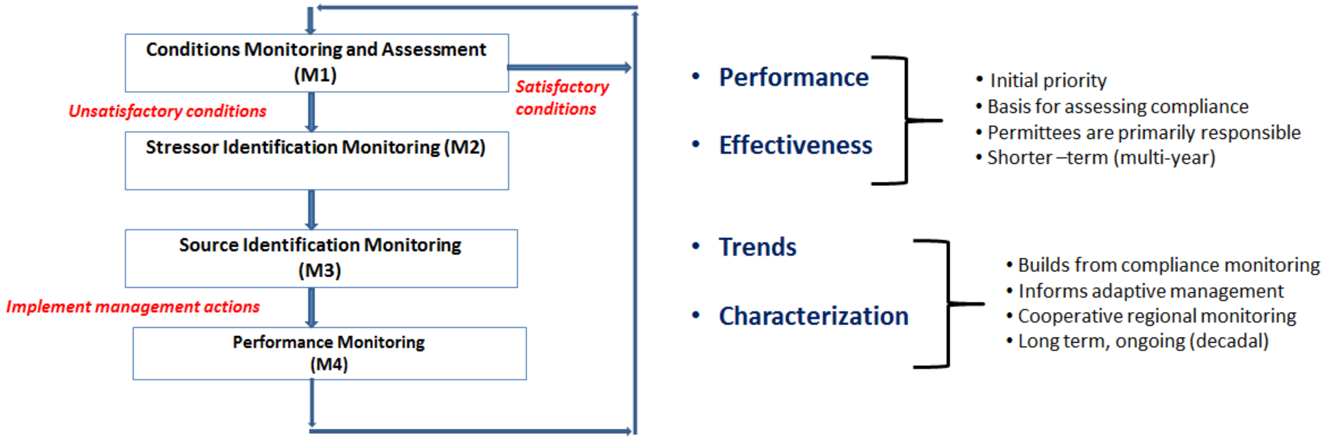

Figure ES-1. Major elements of hydromodification monitoring. General framework (left) and phasing (right)

Addressing all elements of the monitoring plan includes two basic designs: targeted and probabilistic sampling. Targeted sites include reference sites, sentinel sites, and sites downstream of specific BMPs or other management actions (e.g. restoration areas). A summary of the relationship between site types and monitoring questions is provided in Table ES-1.

Table ES-1. Relationship between type of monitoring site and management questions addressed.

	Type of Site	**Monitoring Questions**	
Reference sites		1. performance	3. effectiveness
	Provide context	5. temporal trends	4. spatial extent of effects
	Differentiate effects from natural variability	6. ambient condition	
BMP monitoring sites		1. performance	
	Evaluate performance relative to goals	3. effectiveness (short term)	
	Evaluate compliance		
Targeted and sentinel sites		2. efficacy of management measures	
	Evaluate effectiveness of management actions	3. effectiveness	5. temporal trends
	Evaluate spatial and temporal trends	4. spatial extent of effects	6. ambient condition
Probabilistic		3. effectiveness (short term)	
	Provide regional context	6. ambient condition	
	Interpret long-term trends		
	Help understand natural variability		
GIS analysis		2. efficacy of management measures	
	Provide spatial context		
	Provide insight into causal factors		

Three types of indicators are recommended for inclusion in hydromodification monitoring plans. Pressure indicators measure factors that can cause a response in the stream channel, such as flow. State indicators measure the physical condition of the stream and should include measures that can provide an early detection of potential channel response, such as shifts in the composition of the bed material or channel morphology. Response indicators measure the ecological endpoints of concern from a management perspective and should include long-term integrative measures of condition, such as benthic macroinvertebrates and algae. The pressure-state-response approach to monitoring includes measures of hydrology, geomorphology, and biology, as shown in Table ES-2.

Table ES-2. Summary of recommended field indicators along with their assessment endpoints and the monitoring questions that they support.

	Variable Type			Assessment Endpoint	Monitoring Questions
	P	S	R		
Hydrologic Indicators					
Stream flow	🟦	🟩		long term flow magnitude and duration	3, 4, 5
BMP inflow and outflow	🟦			discharge magnitude and duration	1, 5
Geomorphic Indicators					
Bed material composition		🟩		substrate size as d_{50}	3, 4, 5, 6
Armoring potential		🟩		dominant substrate type and interstitial material	3, 4, 5, 6
Grade control		🟩		presences, spacing and condition of grade control	3, 4, 5, 6
Incision/downcutting risk		🟩		potential specific stream power relative to d_{50}	3, 4, 5, 6
Probability of mass wasting		🟩		critical bank height and bank angle	3, 4, 5, 6
Evidence of fluvial erosion		🟩		evidence of erosion at the toe of slope	3, 4, 5, 6
Consolidation of bank material		🟩		field penetration tests of banks	3, 4, 5, 6
Channel width:valley width		🟩		active channel vs. floodplain	3, 4, 5, 6
Channel Evolution Model class		🟩		field observations of CEM class	3, 4, 5, 6
Channel geometry		🟩		channel cross-sections and longitudinal profile	1, 3, 4, 5
Physical Habitat Assessment (PHAB)	🟦	🟩		standard PHAB metrics	3, 4, 5, 6
Biologic Indicators					
Benthic macroinvertebrates			🟧	IBI, component metrics, functional groups	3, 4, 5, 6
Stream algae			🟧	IBI, component metrics, functional groups, biomass	3, 4, 5, 6
California Rapid Assessment Method	🟦	🟩	🟧	index score, attribute scores, metric scores	3, 4, 5, 6

Hydromodification monitoring should be a component of a larger integrated management program and should be prioritized in the context of other monitoring efforts (e.g. water quality, bio-objectives). Much of the baseline information necessary for the design of effective monitoring programs can be obtained by up-front watershed analysis. Watershed assessment also provides insight into the historic and contemporary causes of hydromodification, which can inform development of monitoring programs. The results of monitoring should be used to refine and adapt management programs over time.

Full benefits of monitoring accrue based on a commitment to long-term (multi-decadal) implementation, which requires infrastructure to support the monitoring program. We estimate the up-front per site cost to be $5,250 and annual recurring per site cost to be $11,500. If all monitoring elements were implemented, the annual cost would range from $456,000 - $569,500 per watershed management area, depending on the number of sites sampled each year. However, $195,000 of that cost would be for ambient condition assessment at probabilistic sites. Monitoring elements can be phased and implemented by different entities in order to defray costs. Furthermore different elements of the monitoring plan can be prioritized based on condition of stream resources being protected and management priorities. The resources necessary to support long-term ongoing monitoring will be beyond the means of individual municipalities or permittees. Long-term implementation needs may be most effectively met through coordination with existing monitoring programs and by sharing existing monitoring infrastructure. Over time, shared data can support causal assessment and provide information to improve hydromodification management.

This document can serve as a foundation to assist state agencies, local jurisdictions, and municipal stormwater permittees in developing detailed hydromodification monitoring plans to address their specific management and reporting needs. This document is intended to provide a set of monitoring elements that can be prioritized for implementation based on local needs; it is not intended to serve as prescriptive plan that should be universally implemented in all instances.

1.0 INTRODUCTION

Ongoing and well-structured monitoring is a critical component of watershed and water-quality management. Monitoring and management programs should be integrated such that practices intended to prevent or mitigate effects of land use on instream conditions should be refined and improved based on monitoring results. Monitoring is also important for assessing compliance with regulatory requirements and for evaluating program effectiveness. However, monitoring is only recently being applied to hydromodification management and with the exception of testing the efficacy of onsite BMP practices, standard approaches have not yet been developed.

Monitoring of hydromodification (i.e. alteration of runoff patterns associated with change in land use that result in change in physical channel conditions) management is particularly critical given the complexity and uncertainty associated with managing effects of hydrologic change on channel structure. Physical changes associated with changes in runoff are difficult to assess because they can result from a combination of contemporary land-use changes, legacy land practices (e.g. grazing), and stochastic events (e.g. floods and fires). Furthermore, channel adjustments can occur dramatically and rapidly after extended periods of apparent stability and can vary over small distances. Separating out the effects of human activity from natural cycles of channel evolution further complicates hydromodification monitoring and requires much longer term monitoring than traditional water quality programs. Due to the relative immaturity of hydromodification management practices as compared to traditional water-quality management, their effectiveness is also less certain. Thus, hydromodification monitoring is essential to allow adaptation and adjustment of early-generation practices to improve their performance over time.

Many stormwater permits require municipalities to develop “hydromodification monitoring plans” as part of their overall management programs. However, little guidance has been provided on the structure and content for these plans. As a result, monitoring plans vary in their approach and intensity. This inconsistency is inefficient, makes inter-jurisdictional comparisons and information sharing difficult, and precludes regional syntheses.

To begin addressing this issue, a statewide technical workgroup commissioned by the State Water Resources Board produced a broad set of recommendations for hydromodification monitoring as part of their report *Hydromodification Assessment and Management in California* (Stein et al. 2012). The proposed monitoring framework presented here is a tiered approach, designed to be executed at different spatial and temporal scales, to inform and help guide management actions.

In the context of hydromodification assessment and management, there are three interrelated purposes for monitoring which will guide the recommendations in this framework:

- Characterizing the conditions of receiving waters downstream of urban development (including any trends in those conditions over time).

- Evaluating the effectiveness of hydromodification controls at protecting or improving the conditions of downstream receiving waters *(and modify them, as needed).

- Setting priorities on the wide variety of hydromodification control practices.

These needs give rise to several interrelated types of monitoring, or elements, all common to many watershed and stormwater monitoring programs. They are typically executed at different spatial and temporal scales, and if well-designed and executed they can collectively help guide management actions. The four elements of the proposed monitoring framework include: 1) **performance monitoring** to evaluate whether a facility or practice meets its design objectives, 2) **effectiveness monitoring** to evaluate how well management actions or suites of actions reduce or eliminate the direct hydromodification impacts on receiving waters, 3) **trends monitoring** to provide an integrative assessment of whether our “endpoint” indicators (physical, chemical, or biological) are showing any consistent and statistically significant change over space and time, and 4) **ambient condition (characterization) monitoring** to provide context of the overall regional or watershed condition of receiving waters. In general, the first and second elements (performance and effectiveness monitoring) can be addressed by multi-year monitoring programs typically managed by municipalities and other local entities. In contrast, the third and fourth elements (trends and ambient condition) must be addressed over longer-time scales (e.g. decadal) through cooperative regional monitoring that must involve multiple entities include state, regional, and local agencies and programs (Figure 1). In practice, not all these elements need to be implemented at the same time or in the same locations. Implementation can be phased or tiered based on specific needs and resource constraints. Furthermore, different entities may be primarily responsible for different elements of the monitoring program (Table 1). In all cases, efforts should be coordinated between programs and entities to maximize the efficiency of implementation and opportunities for information sharing.

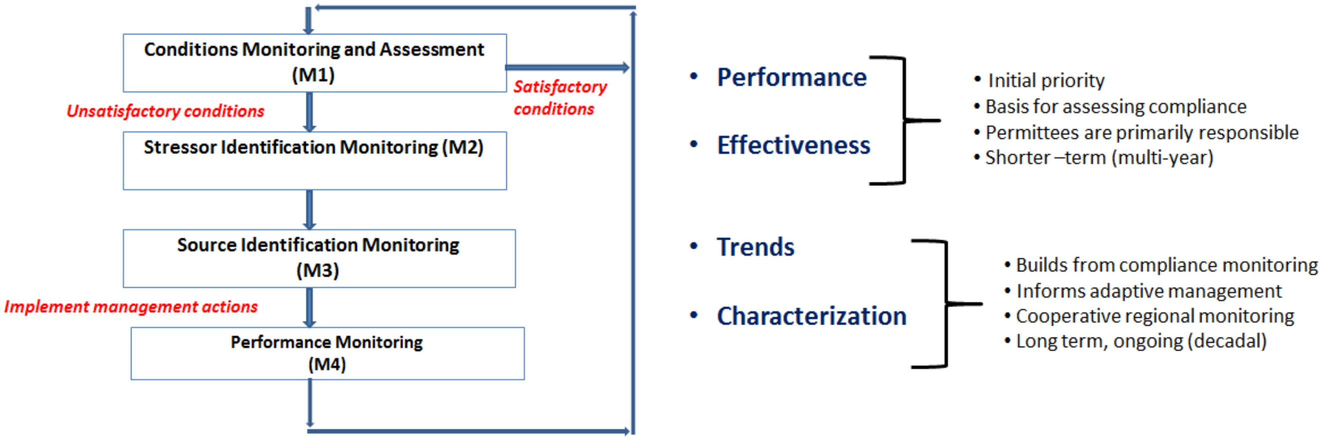

Figure 1. Major elements of hydromodification monitoring. General framework (left) and phasing (right)

Table 1. Phasing and different responsibilities for elements of hydromodification monitoring.

Timeframe	Programmatic: State and Regional Water Boards	Local: City and County Jurisdictions
Short-term (<10 years)	• Define the watershed context for local monitoring (at coarse scale) • Evaluate whether permit requirements are making positive improvements	• Evaluate whether specific projects/ regulations are meeting objectives • Identify the highest priority action(s) to take
Long-term (1+ decades)	• Define watershed context and setting benchmarks for local-scale monitoring (i.e., greater precision, if/as needed) • Demonstrate how permit requirements can improve receiving-water "health," state-wide (and change those requirements, as needed)	• Evaluate and demonstrate whether actions (on-site, instream, and watershed scale) are improving receiving-water conditions • Assess program cost-effectiveness • Identify any critical areas for resource protection

The goal of this document is to build on the general recommendations provided by Stein et al. (2012) by providing more specific recommendations for hydromodification monitoring plans that address a set of common management questions in a consistent manner. This document can serve as a foundation to assist state agencies, local jurisdictions and municipal stormwater permittees in developing detailed hydromodification monitoring plans to address their specific management and reporting needs. This document is intended to provide set of monitoring elements that can be prioritized for implementation based on local needs; it is not intended to serve as prescriptive plan that should be universally implemented in all instances.

1.1 Hydromodification Monitoring in Context of Larger Management Programs

Hydromodification monitoring should be a component of a larger integrated management program (Figure 2). Watershed assessments conducted during development of integrated management programs provide much of the baseline information necessary for the design of effective monitoring programs. The location and intensity of monitoring (i.e. what gets monitoring at various locations) will depend on the stream types, opportunities and constraints identified during initial assessments. Similarly, the choice and location of management actions informs where monitoring should occur and what indicators are measured. Watershed assessment also provides insight into the historic and contemporary causes of hydromodification, which can inform development of monitoring programs. Therefore, monitoring programs should be developed using information compiled during these earlier efforts. The results of monitoring should be used to refine and adapt management programs over time.

It is also important to recognize that streams will respond to a variety of natural and anthropogenic stressors over varying time scales. Consequently, changes in condition detected as a result of a hydromodification monitoring program will need to be placed in the context of other stressors in the contributing drainage area (and their proximity to the stream reach being evaluated), climatic cycles, and recent disturbances (e.g. floods or fires). Management responses derived from hydromodification monitoring results should account for these factors and utilize other stream management programs as appropriate. Similarly, monitoring priorities should be established based on a consideration of the most important stressors acting on an individual watershed.

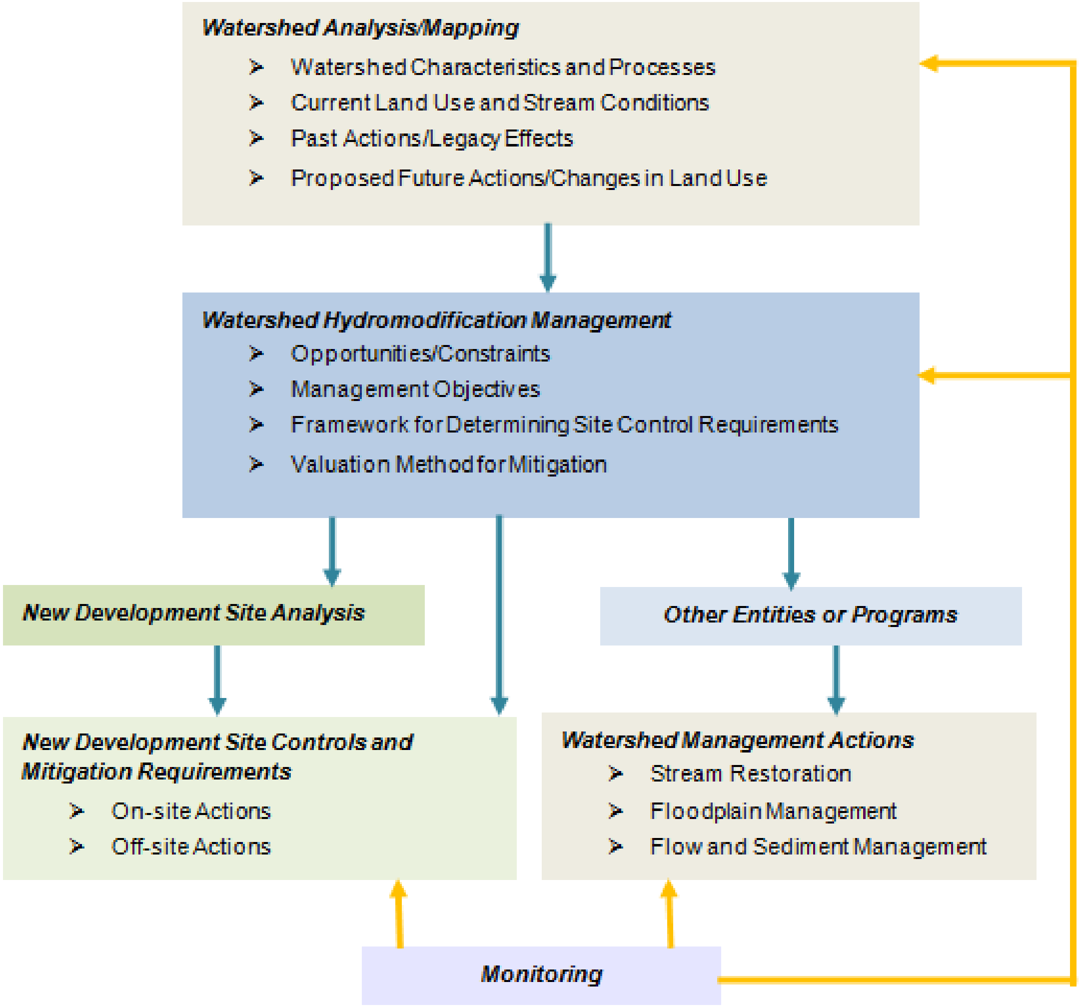

Figure 2. Framework for integrated hydromodification management.

1.2 Key Components of a Hydromodification Monitoring Plan

A successful monitoring plan will be flexible and adaptable, and will have a direct connection to management decisions. There are generally two priority management areas that drive the design of monitoring programs. The first is an evaluation of overall watershed and stream conditions, including stream health and beneficial uses. In its broadest sense, “health” encompasses chemical, physical, and biological integrity and should be evaluated using multiple indicators at multiple spatial scales (i.e., ranging from the entire landscape to site-specific). Hydromodification management is one of many important factors affecting watershed and stream health; therefore, hydromodification monitoring should be well integrated with regional programs that assess overall watershed and stream health. Causal assessment or stressor identification that may be conducted when conditions do not meet agreed-upon goals and targets may identify hydromodification control as a priority action, increasing the importance of integrating hydromodification monitoring data into larger overall regional programs. The first priority management area should be addressed at a cooperative programmatic scale, involving multiple entities at state, regional, and local agencies and programs.

The second priority area is an assessment of compliance with regulatory requirements. This may include monitoring performance of specific BMPs or management measures and evaluation of whether targets, objectives, and beneficial uses have been met in receiving waters. Permittee-directed hydromodification monitoring will typically focus on this second priority area. However, as stated above, because regulatory compliance may be obtained by achieving overall watershed health, compliance and watershed condition monitoring must be coordinated at every level and by all responsible parties.

To address the two priority management areas discussed above, a Hydromodification Monitoring Plan should include the following attributes:

> Plan is question-driven and has clear assessment endpoints. All components of design and data collection should support the core management questions.
>
> Plan is multidimensional. Different factors should be designed to answer the various core questions (e.g. receiving water monitoring, BMP monitoring).
>
> Multiple indicators are used. Using multiple hydrologic, physical, and biological indicators to assess effects of management actions provides a more robust assessment and increases the ability to diagnose potential stress-response relationships. In some cases the primary stressors may be something other than hydromodification. It is important to note that some indicators may only apply in certain types of streams (e.g. benthic invertebrates in wadeable streams).
>
> Plan is modular. A modular design allows elements to be implemented in a phased or incremental manner and to build on existing programs. Different aspects can be implemented based on interest and management information needs. It may not be necessary (or desirable) in some cases to implement all elements of the monitoring program concurrently. A modular design also allows the level of effort to be adjusted commensurate with factors such as the value of resources at risk, the level and certainty of effects, monitoring priorities, and the availability of funding. It also allows for iterative refinement of the overall program based on early monitoring results.
>
> Plan is consistent with other regional programs. Common monitoring protocols allow for consistent application from project to project and across different programs. Data consistency will also allow information to be compiled across programs to build larger, more robust, long-term monitoring data sets that can be readily compared. A consistent regional approach will require development of common quality control procedures and information management/data transfer protocols.

Plan is adaptive. Monitoring data should be directly tied back to the core questions in order to assess the effectiveness of management actions. Monitoring results should be used to inform changes in the selection and implementation of management strategies, to support regional watershed models, and to adapt future monitoring priorities. This will require coordination between the various entities implementing hydromodification monitoring. Adaptive feedback is particularly important for hydromodification because management techniques are relatively new and approaches are expected to evolve over time based on early implementation experience (Figure 3).

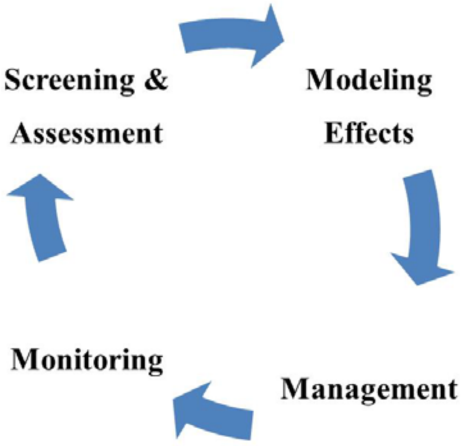

Figure 3. Adaptive feedback relationship between monitoring and other elements of hydromodification management.

1.3 Primary Monitoring Questions

The specific monitoring design is guided by monitoring for each of the four elements discussed above. When developing a tiered approach to hydromodification monitoring it is advisable to analyze the highest priority element(s) and focus resources in that area. Six primary monitoring questions are recommended in order to adequately address all elements of the monitoring framework keeping in mind that every Hydromodification Monitoring Plan should be designed to meet local needs. The following management questions should be considered in the plan development process.

1.3.1 Questions Answered through Local-Agency Led Monitoring over Shorter Timeframes

Performance Assessment

1) How well do various BMPs, control strategies and management measures perform relative to their design expectations and in light of how well they are maintained?

2) What factors influence the efficacy of hydromodification management strategies?

Effectiveness Assessment

3) How effective are specific management strategies at protecting the physical and biological integrity of streams from the effects of hydromodification (in the context of other watershed stressors)?
    a. How do these effects compare to patterns at unimpacted "reference[1]" sites?
    b. Are the management strategies sufficiently protective of all stream types?
    c. How does effectiveness vary by stream type (e.g. substrate, planform, slope)?

1.3.2 Questions answered through regional/programmatic monitoring over longer timeframes

Spatial and Temporal Trends Assessment

4) What is the spatial footprint of response to hydromodification effects or management actions relative to discharge locations?
    a. How far up or downstream do potential effects of hydromodification persist?

5) How do responses to hydromodification management vary over time?
    a. What is the effect of natural rainfall and runoff patterns on stream response in the presence or absence of management measures?
    b. How long do "restored" or "rehabilitated" stream reaches take to recover following remediation?
    c. How do responses vary based on stream type (e.g. substrate, planform, slope) and environmental setting (e.g. watershed position relative to upstream land use, floodplain condition)?

Ambient (Characterization) Monitoring

6) What is the physical and biological condition of streams relative to established regulatory or management objectives?
    a. How does condition vary by stream type (e.g. substrate, planform, slope) and environmental setting (e.g. watershed position relative to upstream land use, floodplain condition)?

Questions #1 to #3 should be the focus of a local agency/permittee-directed hydromodification monitoring program, but can benefit by regional cooperation with other entities. Questions #4 to #6 should be addressed through coordination of hydromodification monitoring with a watershed or regional monitoring program involving multiple entities at the state, regional and local levels. The latter questions can only be answered through long-term sustained monitoring. This is particularly true since hydromodification effects may only occur under specific circumstances (e.g. storms of certain size or duration). Long-term (multi-decadal) data sets will be necessary to separate effects of management actions (or lack thereof) from natural variability in channel conditions. It should be noted that the approach to answering these questions can also apply to the objectives of other monitoring programs

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[1] Reference is currently defined as "minimally affected by human activities" in the Reference Condition Management Program (Ode et al. 2009). Where possible, regional reference sites can be used.

under NPDES permits, watershed plans, or regional monitoring programs. Integration of hydromodification monitoring with other monitoring efforts should be a priority, with the ultimate goal being an integrated watershed-scale monitoring and assessment program. Such a program would allow for sharing of reference sites, sampling sites and information across programs and jurisdictions in order to allow leveraging of effort/information and more coordinated management responses. This involves mapping the location and type of various monitoring efforts and developing mechanisms for data sharing. Monitoring implementation should include time to develop and sustain the necessary inter-departmental and/or inter-agency coordination associated with the integrated monitoring approach.

It is important to note that hydromodification has the potential to affect all water body types; therefore, hydromodification management and the associated monitoring should address potential effects to all streams and receiving waters. Because streams are most directly affected by hydromodification, they have been the focus of current regulatory requirements and, therefore, most management programs. Consequently, this document emphasizes tools and approaches applicable to fluvial systems, which are broadly defined to include wadeable streams, large rivers, headwater streams, intermittent and ephemeral drainages, and alluvial fans (although new specific tools may be necessary for assessment and management of alluvial fans). We recognize, however, that hydromodification can also affect nearshore and coastal environments, including bays, harbors, and estuaries, by altering estuary channel structure, water quality, sand delivery, siltation, and salinity. These effects have been less extensively studied or documented and have received substantially less attention in current hydromodification requirements. Future efforts should more directly address hydromodification effects to all receiving waters, but the information is not presently available to provide equally comprehensive guidance here.

1.4. Adaptive Monitoring through Hypothesis Testing

As with all monitoring programs, this plan should be adaptive. Early monitoring results should be used to refine questions and the associated monitoring design over time. For a plan to be truly adaptive the core questions must be predicated on a set of testable hypothesis. Not every hypothesis can be fully tested at all times; however; they provide a consistent framework for the development of adaptive monitoring designs.

1.4.1 Hypotheses that Drive the Monitoring Plan

Performance Assessment

> BMPs will perform as designed over a range of storm conditions and will be maintained adequately to perform effectively.

Effectiveness Assessment

> Specific management strategies can help protect the physical and biological integrity of streams from the effects of further hydromodification.
>
> Flow duration control is better than no control or peak flow control at reducing impacts, but effectiveness will be influenced by site conditions.

Management practices that contribute to dynamic channel stability, also contribute to healthy biotic communities.

The effectiveness of flow duration control based BMPs at preventing excessive erosion/channel instability will vary based on the degree of change in sediment supply.

Spatial and Temporal Trends Assessment

Hydromodification management will promote dynamic stability of channels and natural fluctuations in cross-section and planform that are similar to streams from minimally impacted areas.

Hydromodification management will protect against upstream or downstream propagation of channel erosion or deposition.

Ambient Condition (Characterization) Monitoring

Hydromodification management measures will allow streams to meet objectives established under watershed plans or regulatory requirements.

Stream or receiving water type, bed-material, slope (landform), and geologic setting, as well as past, present, and future land use determine overall watershed processes and influence the degree to which hydromodification effects may be manifested.

2.0 GENERAL MONITORING APPROACH

Answering the core questions requires different design approaches, several suites of indicators, and varying time scales, frequencies and durations. The basic monitoring elements are summarized in Table 2 and discussed in detail in the following sections. *As noted above, the overall monitoring program can be implemented in a modular or phased manner and does not need to be implemented all at once.* Specific questions can be addressed as they become relevant or as preliminary data suggests that more intensive monitoring would be beneficial. Also as noted above, the permittee-directed monitoring should focus on performance effectiveness assessment. Permittees should cooperate with integrated regional monitoring programs to answer spatial and temporal trends and overall characterization questions. It is important to note that separating the effect of hydromodification management over time from natural patterns of channel evolution will require long-term (multi-decadal) monitoring, which is often beyond the timeframe typically associated with traditional water quality monitoring programs.

Design of a monitoring program (as well as decisions regarding management actions) can benefit from watershed analysis that summarizes the general condition of various areas, and identifies opportunities and constraints. Watershed analysis should begin with a documentation of watershed characteristics and processes, and past, current, and expected future land uses. The current condition of streams and their response trajectories should be examined in the context of past alterations to streamflow, sediment delivery, and direct manipulations of physical habitat such as channel straightening and armoring. The analysis should lead to identification of existing opportunities and constraints that can be used to help prioritize areas of greater concern, areas of restoration potential, infrastructure constraints, and pathways for potential cumulative effects. The combination of watershed and site-based analyses should be used to establish clear objectives to guide monitoring and management actions. These objectives should articulate desired and reasonable physical and biological conditions for various reaches or portions of the watershed and should prioritize areas for protection, restoration, or management. Strategies to achieve these objectives should be customized based on consideration of current and expected future channel and watershed conditions. For example, stream restoration is probably not a viable option if substantial changes in upstream water and sediment delivery are anticipated in the future. A one-size-fits-all approach should be avoided. Even where site-based control measures, such as flow-control basins, are judged appropriate, their location and design standards should be determined in the context of the watershed analysis. Maps and landscape-scale data produced as part of the watershed analysis should inform the hypothesis and management questions upon which monitoring programs are based. Similarly, interpretation of monitoring data should rely on insights and understanding provided by watershed analysis. Watershed analysis provides a critical foundation for monitoring programs, but is often neglected due to time or resource constraints. Efforts should to include this important step will provide long-term benefits in terms of program design and interpretation of results.

Table 2. Summary of recommended monitoring design elements.

	Monitoring Question	Design	Location criteria	Season	Frequency	Duration	Sampling triggers	Indicators
Performance Assessment								
1)	How well do various controls strategies and management measures perform relative to their design expectations	targeted	location of regional or site-specific BMPs + undeveloped reference sites	storm season	annually for first 5 years after installation	periodically after first 5 years based on performance	enhance monitoring following large storms or substantial changes in land use	inflow and outflow rates from BMPs over storm duration, flow and x-secs immediately d/s of BMPs + comparable reference site data
2)	What factors influence the efficacy of hydromodification management strategies?	map/GIS based + review of targeted data	watershed wide GIS + evaluation of data from specific settings	N/A	once at the start of monitoring program and then updated periodically based on changes in land use/infrstructure		substantial changes in land use, infrastructure or other watershed attributes	***GIS*** , supported by field based stressor identification
Effectiveness Assessment								
3)	How effective are specific management strategies at protecting the physical and biological integrity of streams from the effects of hydromodification?	Targeted w/**BACI** design	upstream and downstream of selected BMPs, multiple locations	dry season and continous flow measures	annually for first 5 years	after yr 5, integrate with regional monitoring	enhance monitoring following large storms or substantial changes in land use	***screening tool measures,*** physical habitat assessment, ***bioassessment,*** channel cross-sections, flow
Spatial and Temporal Trends Assessment								
4)	What is the spatial footprint of hydromodification responses relative to discharge locations?	targeted	upstream and downstream of selected BMPs, multiple locations	dry season	every 2-3 years	ongoing	increase frequency following large storms & substantial change in land use	***screening tool measures,*** physical habitat assessment***, bioassessment,*** channel cross-sections
5)	How do responses to hydromodification management vary over time?	targeted	sentinal or integrator sites + reference sites	dry season and continous flow measures	every 2-3 years	ongoing	none	***screening tool measures,*** physical habitat assessment, ***bioassessment,*** channel cross-sections, flow
Characterization Monitoring								
6)	What is the physical and biological condition of streams relative to established regulatory or management objectives?	probabalistic + sentinal sites	stratified by stream type or management unit + reference and integrator sites	dry season	annually in a rotating design	ongoing	possible intensification following stochastic events such as floods or fires	***screening tool measures*** , physical habitat assessment, ***bioassessment***

screening tool measures = cross sections, bed material composition, floodplain width, bank height & angle, grade control, Channel Evolution Model (CEM) class

bioassesment = benthic macroinvertebrates, algae, California Rapid Assessment Method (CRAM)

GIS = land use, structures, channel types, Channnel Evolution Model (CEM) classes if available

BACI = Before-after-control-impact

2.1 Monitoring Design and Site Selection/Location Considerations

The overall monitoring plan includes two basic designs: targeted and probabilistic sampling. Targeted sites include reference sites, sentinel sites, and sites downstream of specific BMPs or other management actions (e.g. restoration areas). A summary of the relationship between site types and monitoring questions is provided in Table 3.

Targeted sites should be selected in order to best evaluate the specific management questions. Targeted sites include those used to evaluate effects of management actions and those that serve as watershed reference sites. In addition, the following general criteria should be considered:

- Appropriate scale: the upstream area should be dominated by, or at least significantly affected by, the management action of interest.

- Responsiveness: at the chosen location, the indicators being measured should be amenable and relatively sensitive to change in response to the management action.

- Representativeness: the results at the chosen location should be credibly extrapolated to "similar" sites, and those sites in aggregate should constitute a widespread (or otherwise important) subset of the landscape as a whole.

- Access: the site should be easily and safely reached by the appropriate personnel and equipment, and with a cost of doing so consistent with the frequency of measurements being made. Any equipment left unattended needs to be secure from theft or vandalism, or must be well-hidden.

Probabilistic sites should be selected at random using methods developed by the USEPA and the Stormwater Monitoring Coalition (SMC; Stevens et al. 1997, USEPA 2002, SCCWRP 2007). Randomly selected sites can be stratified into groups based on physical setting, management priorities, or specific assessment questions. An existing "master sample draw" has been developed in southern California as part of the SMC's regional watershed monitoring program. This existing draw can be used to provide an unbiased set of site locations to support the ambient characterization monitoring under Question #1. This will also facilitate coordination of hydromodification monitoring with existing regional and NPDES required monitoring.

Routine review of aerial and ground-based photography can also be a powerful and relatively inexpensive tool to help select probabilistic sites and support monitoring programs. Aerial photography can be used to identify areas of the watershed analysis that require updating due to changed conditions. Aerial photographs can be used to evaluate floodplain width, planform changes, channel migration, and floodplain obstructions or constrictions (either natural or anthropogenic). This information can provide a screening level evaluation of condition that can be used to prioritize locations for more specific ground-based monitoring. Aerial photographs are also important for reconnaissance of candidate sites for ambient condition assessment (Question #6). They can also provide a general overview of the condition of the site over time (e.g. before and after construction of a BMP), can help refine specific field sampling locations, and are a relatively easy way to support assessments of potential causes of effects (Question #2), spatial extent of effects (Question #4) and trends (Question #5).

Efforts should be made to coordinate the locations of both probabilistic and targeted hydromodification monitoring sites with sites being used for other monitoring programs. This may or may not be possible given the specific needs of different programs in terms of site types, flow conditions, locations etc. However, where possible sharing sites between programs can increase efficiency and reduce costs. In addition, Questions #1, #5, and #6 involve comparison to relatively unimpacted reference sites as a means of increasing the power to detect effects (Loftis et al. 2001). Selection of these sites can be based on the existing Reference Condition Management Program (Ode et al. 2009) and informed by the watershed analysis described above.

Table 3. Relationship between monitoring questions and types of sites used to answer each question. Shading indicates that the specific site type is used to answer the indicated monitoring question.

	Monitoring Question					
	Performance		Effectiveness	Spatial		Characterization
	1	2	3	4	5	6
Type of Site	How well do various controls strategies and management measures perform relative to their design expectations	What factors influence the efficacy of hydromodification management strategies?	How effective are specific management strategies at protecting the physical and biological integrity of streams from the effects of hydromodification?	What is the spatial footprint of hydromodification responses relative to discharge locations?	How do responses to hydromodification management vary over time?	What is the physical and biological condition of streams relative to established regulatory or management objectives?
Reference sites	developed sites with no BMPs		▨		▨	▨
Provide context						
Differentiate effects from natural variability						
BMP monitoring sites	▨		short term			
Evaluate performance relative to goals						
Evaluate compliance						
Targeted and sentinel sites		▨	short and long term	▨	▨	▨
Evaluate effectiveness of management actions						
Evaluate spatial and temporal trends						
Probabilistic			Long-term			▨
Provide regional context						
Interpret long-term trends						
Help understand natural variability						
GIS analysis		▨				
provide spatial context						
provide insight into causal factors						

2.2 Monitoring Season, Duration, and Frequency

Most monitoring questions can be answered via data collected during the non-storm (dry season). The exception is the evaluation of BMP performance and other measures of stormflow or sediment transport, which will typically occur during the storm flow conditions. Questions #1 to #3 can initially be evaluated over the five-year timeframe associated with a typical permit cycle; however, in many cases several permit cycles may be necessary to fully address these questions. The time necessary to answer these questions may be longer based on several factors that are often out of the control of permittees. For example, BMP performance and stream response may require rainfall patterns necessary to trigger specific size flow events, which may only occur periodically. Second, the pace of development and redevelopment may influence when BMPs or other management measures are constructed and can then be monitored.

Questions 4-6 will need to be evaluated over longer time periods (i.e. multiple decades) as part of a regional monitoring program; often relatively long monitoring periods (>10 - 15 years) are required to detect change (Loftis et al. 2001). A subset of sites used to address Questions #1 to #3 may be rolled into long-term regional monitoring programs. *Finally, the value of long-term flow data should not be underestimated, particularly for evaluating the effects of hydromodification management. Establishing flow monitoring stations at key locations should be a high priority for hydromodification monitoring programs*.

2.3 Monitoring Indicators

Field indicators need to meet several objectives. First, the monitoring program should include indicators of pressure, state and response (Figure 4). Pressure indicators measure factors that can cause a response in the stream channel, such as flow. Stream flow is the first link in the causal chain between management practices and stream response. State indicators measure the physical condition of the stream and should include measures that are able to provide an early detection of potential channel response, such as shifts in the composition of the bed material or channel morphology. Physical habitat is determined by interactions between flow and channel structure; therefore, it is it necessary to monitor state indicators of the geomorphic characteristics that mediate the effects of hydromodification on biological endpoints. Response indicators measure the ecological endpoints of concern from a management perspective, and should include long-term integrative measures of condition, such as benthic macroinvertebrates and algae. The pressure-state-response approach to monitoring means that the monitoring program will include measures of hydrology, geomorphology, and biology, as described below.

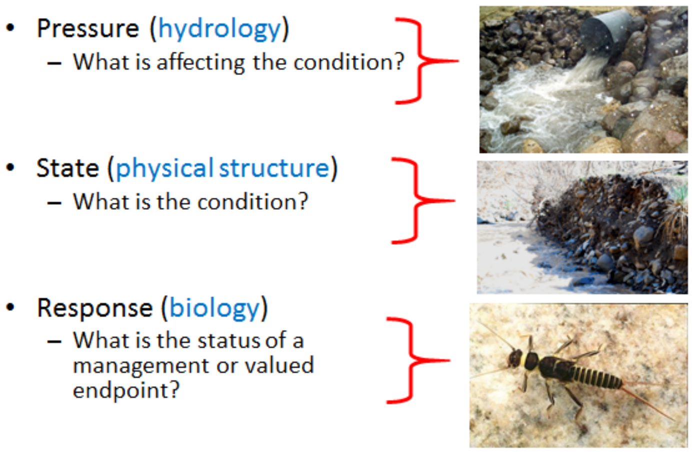

Figure 4. Pressure-state-response approach to monitoring.

In a general sense, response variables measure the overall "health" of a stream and are used to make decisions as to whether intervention is necessary to improve overall condition. State variables provide insight into the physical conditions that affect biological response variables. Together, state and response variables can be used to help prioritize where management action is necessary and how intensive that management action should be. Pressure variables provide insight into "what needs to be changed" to improve stream condition, and (together with state variables) can be used to guide specific management responses (e.g. altering flow conditions).

It is important to note that many stream channels of concern that are impacted by hydromodification will be ephemeral or intermittent, particularly in Southern California. Some commonly used bioassessment indicators (e.g. benthic macroninvertebrates) may not be usable in extremely dry streams (such as those without persistent baseflow through the spring). In such cases, other indicators such as those included in the California Rapid Assessment Method (CRAM; CWMW 2012) will apply. In addition, monitoring entities may want to include general habitat assessments, including several metrics contained in the California Physical Habitat Protocol (Ode 2007) to evaluate biological condition of streams. As new bioassessment indicators for intermittent and ephemeral streams are developed, they can be added into existing programs.

Stressors other than hydromodification (e.g. pollutant discharges, invasive species infestations) may contribute to changes in stream condition. Consequently, many of the indicators used may be responding to multiple factors. This should be accounted for during analysis and interpretation of monitoring data and should be used to identify opportunities for cooperation with other monitoring and management programs.

The selected indicators should be practical from a cost and logistics perspective, have an established scientific basis, have direct ties to designated uses, have existing protocols available, and provide information that can serve broader monitoring objectives beyond hydromodification assessments. In many cases, the recommended indicators may already be included in existing monitoring programs. Recommended field indicators are summarized in Table 4 and discussed in detail below.

Table 4. Summary of recommended field indicators along with their assessment endpoints and the monitoring questions that they support.

	Variable Type			Assessment Endpoint	Monitoring Questions
	P	S	R		
Hydrologic Indicators					
Stream flow	🟦	🟩		long term flow magnitude and duration	3, 4, 5
BMP inflow and outflow	🟦			discharge magnitude and duration	1, 5
Geomorphic Indicators					
Bed material composition		🟩		substrate size as d_{50}	3, 4, 5, 6
Armoring potential		🟩		dominant substrate type and interstitial material	3, 4, 5, 6
Grade control		🟩		presences, spacing and condition of grade control	3, 4, 5, 6
Incision/downcutting risk		🟩		potential specific stream power relative to d_{50}	3, 4, 5, 6
Probability of mass wasting		🟩		critical bank height and bank angle	3, 4, 5, 6
Evidence of fluvial erosion		🟩		evidence of erosion at the toe of slope	3, 4, 5, 6
Consolidation of bank material		🟩		field penetration tests of banks	3, 4, 5, 6
Channel width:valley width		🟩		active channel vs. floodplain	3, 4, 5, 6
Channel Evolution Model class		🟩		field observations of CEM class	3, 4, 5, 6
Channel geometry		🟩		channel cross-sections and longitudinal profile	1, 3, 4, 5
Physical Habitat Assessment (PHAB)	🟦	🟩		standard PHAB metrics	3, 4, 5, 6
Biologic Indicators					
Benthic macroinvertebrates			🟧	IBI, component metrics, functional groups	3, 4, 5, 6
Stream algae			🟧	IBI, component metrics, functional groups, biomass	3, 4, 5, 6
California Rapid Assessment Method	🟦	🟩	🟧	index score, attribute scores, metric scores	3, 4, 5, 6
P: *pressure variable*					
S: *state variable*					
R: *response variable*					

2.3.1 Hydrologic Indicators

Stream Flow

Stream flow can be a pressure variable in that it affects physical and biological condition of the channel. It can also be a state variable to the extent that it describes the environment in which biota live and directly respond. Continuous flow monitoring is an important element of effectiveness monitoring. In addition, the magnitude and duration of erosive flow events at targeted locations should be measured during storm events; monitoring should commence prior to increase in flow in response to stormwater runoff and continue through peak flow until discharge falls below a threshold of significant sediment transport. Flow should be measured at a portion of the channel with a well-defined cross-section, with relatively uniform flow, and that does not experience hydraulic backwater effects, that can be used to rate flow (i.e. relate water surface elevation to discharge). These constraints should be considered when selecting monitoring locations in channels with multiple or distributed flow paths. Technical guidance on open channel flow measurement methods is available from the USGS, USDA Bureau of

Reclamation, USEPA and numerous State water-quality monitoring program websites. A summary of guidance on measuring streamflow is provided in Appendix A.

BMP Inflow and Outflow

Outflow characteristics from site-specific or regional BMPs are pressure variables. Inflow and outflow should be monitored following representative storms and compared to the design standards of the BMP or basin. A subset of representative BMPs or other facilities could be subject to ongoing monitoring beyond the initial performance assessment period. Consideration must be given to monitoring requirements during BMP design/site permitting/BMP construction, in order to accommodate continuous outflow measurements. Technical guidance on pipe flow measurement methods is available from the USGS, USDA Bureau of Reclamation, USEPA and numerous State water-quality monitoring program websites.

As a pressure variable, stream flow and BMP outflow are factors that can be directly affected by management measures. Therefore, they can be used as proximate measures of the effect of those management measures and as compliance points.

2.3.2 Geomorphic Indicators

Screening Tool Indicators

The Hydromodification Screening Tool developed by SCCWRP and Colorado State University (Bledsoe et al. 2010, 2012) provides a set of relatively simple to measure, but quantitative, field indicators designed to provide a rapid assessment of the relative susceptibility of a specific stream reach to effects of hydromodification. These same field indicators should be used as state variables to assess general condition of a stream reach relative to hydromodification effects. The screening tool includes the following field indicators, with more detail available in Bledsoe et al. 2010:

- Bed material composition, expressed as d_{50}
- Armoring potential measured as combination of dominant substrate type and interstitial material
- Presence and condition of grade control
- Incision/downcutting risk based on the potential specific stream power relative to d_{50}
- Probability of mass wasting based on critical bank height and angle
- Evidence of fluvial erosion at the toe of bank
- Consolidation of bank material
- Width of the active channel relative to the overall valley width
- Channel condition relative to the state of the Channel Evolution Model (Hawley et al. 2012)

Channel Geometry

Channel cross-sectional area and longitudinal profile is a state variable and often serves as an assessment endpoint for determining hydromodification response or recovery. Geomorphic surveys of channel cross-sections should be guided by the field protocol of Harrelson et al. (1994) and performed by a knowledgeable/experienced survey crew using a total station and data collector or level/rod. Surveys should occur over 10 bankfull channel widths. Surveys should include at least three cross-sectional profiles (upper, mid, lower reach) that extend to either the valley edge or above the apparent 25 year floodplain. Channel surveys and photo points looking upstream and downstream should be tied to "permanent" control points or monuments tied to a geodetic framework (such as NAD 27 or 83).

Physical Habitat Assessment (PHAB)

PHAB data can serve as a pressure or state variable. The PHAB protocol (Ode 2007) is part of the standard bioassessment procedures already conducted as part of many compliance and ambient monitoring programs. PHAB measures a series of physical channel characteristics, riparian, substrate, and human alterations along 11 transects over a 150 to 200 m stream reach. These data are converted to "metrics" used to evaluate the general condition of physical habitat and the suitability of the stream to provide habitat for benthic macroinvertebrates. These same metrics provide insight into stability or response of the stream channel to hydromodification effects.

State variables are monitored for several reasons: 1) they provide a measure of the physical condition of channels relative to hydromodification and thus can be used as measures of compliance or effectiveness of management measures; 2) they indicate areas that require management attention and therefore help guide and prioritize management measures; and 3) they help link pressure variables, such as flow, with response variables, such as biology and therefore help provide mechanistic insight how stream ecosystems respond to hydromodification and hydromodification management.

2.3.2 Biologic Indicators

Benthic Macroinvertebrates

Benthic macroinvertebrate community composition and indices of biological integrity (IBIs) are response variables that can be used to assess overall health of instream communities. As with PHAB, benthic macroinvertebrate assessments are routinely conducted as part of many existing ambient assessment and compliance monitoring programs. Benthic macroinvertebrates shall be collected using the multi-habitat method described in the SWAMP protocol (Ode 2007). Identifications will be done according to the Standard Taxonomic Effort Level 2 for California benthic macroinvertebrates, as described in Richards and Rogers (2007). Benthic macroinvertebrate assessments can be done in perennial wadeable streams and non-perennial streams with persistent baseflow through the spring sampling index period. Other biological indicators such as fish or plants will need to be developed and/or used in streams with deep water flow and in ephemeral streams.

Stream Algae

Bioassessment tools based on instream algae are another response variable often used in concert with benthic macroinvertebrates to assess overall instream health relative to known stressors. Algal bioassessment includes measures of soft-bodied algae, cyanobacteria, and diatoms. Assessments are typically conducted in two ways; biomass and taxonomic identification. Algae are collected using the multi-habitat method described in the SWAMP protocol (Fetscher et al. 2009). As with the benthic invertebrates, algal assessment can be done in perennial wadeable streams and non-perennial streams with persistent baseflow through spring sampling index period.

California Rapid Assessment Method (CRAM)

CRAM assessments include pressure, state and response variables. CRAM is a standardized assessment method that typically can be completed by a two-person crew in less than four hours in the field per site. It evaluates general conditions relative to four attributes (landscape context, hydrology, physical structure, biological structure) based on a set of structured field observations and includes an evaluation of stressors that may affect condition. CRAM applies to perennial and non-perennial streams and assessments are conducted during the spring-summer plant growing season. Protocols for CRAM assessments are provided in the CRAM user's manual version 6.0 (CWMW, 2012) and on the CRAM website at www.cramwetlands.org.

Response variables measure the biological health of streams, which is the ultimate desired management endpoint. A primary goal of water quality programs is to protect and restore instream biology, so measuring it directly is a direct measure of success. Furthermore, regulatory programs, such as freshwater bio-objectives, increasingly use biological endpoints as compliance measures.

2.3.4 GIS Indicators

GIS indicators should be developed as part of the watershed analysis described above and should include factors that both control and affect watershed processes. Key GIS indicators will include:

- Topography and valley slopes based on the digital elevation models
- Surficial geology from USGS or the California Geologic Survey
- Soil types and infiltration/drainage/runoff characteristics from NRCS or local data
- Land use/land cover from the National Land Cover Database or higher resolution local data
- Existing channel conditions and mapped channel structures
- Channel widths relative to floodplain widths (including floodplain restrictions and obstructions)
- Existing flood control facilities and water quality or flood control basins
- Locations of BMPs, restoration projects and other management actions
- Footprint of regional fires (updated annually)
- Areas of particular environmental, economic, social, or management concern

3.0 SPECIFIC MONITORING APPROACHES

Each of the six monitoring questions (listed in Section 1.3) includes specific design considerations such as specific site selection criteria, frequency and duration of sampling, triggers to initiate monitoring events, and priority indicators. These elements are discussed for each question in the subsections below. As noted above, the elements should be viewed as modules that can be implemented in various combinations and at various timeframes based on need and resource constraints. It is not necessary (nor may it be desirable) to implement all elements at the onset of a monitoring program. Phased implementation allows for adaptation and prioritization. Hydromodification monitoring should be coordinated with other monitoring efforts where there is overlap (e.g. other stormwater programs, water quality certifications under Section 401 of the Clean Water Act, ambient stream monitoring).

Performance Assessment (Local Agency/Permittee Directed)

3.1 Question #1

How well do various controls strategies and hydromodification management measures perform relative to their design expectations?

This is the main question used to evaluate the performance of representative BMPs or other hydromodification management measures. Effectiveness is evaluated by measuring inflow and outflow characteristics from management areas (e.g. floodplain restoration sites, basins)[2] or BMPs, relative to design parameters. Where possible, continuous flow monitoring should be conducted for the first several years following BMP installation and as an ongoing measure for large or regional BMPs. Understanding the performance of management measures is an important component of regulatory compliance. Results from this question should be used to adapt and improve management practices over time in order to inform future decisions about the design and placement of BMPs. Performance of management measures is a core element of adaptive management that will increase the ability to protect and restore stream channels into the future.

3.1.1 Design and Location Criteria

BMP performance is best achieved through targeted sites located at the outflow of BMPs or other management measures. . In some instances, BMP performance assessment may be pooled regionally instead of conducted within each Watershed Management Area. Data from these sites is used to evaluate their performance relative to design criteria and in the receiving channel downstream of the BMP. Post construction/implementation, representative BMPs should be monitored to determine if they are performing as intended and/or if modifications are necessary to achieve desired performance. Over the long-term a subset of the representative sites could be monitored to aid in evaluation of trends and long-term performance patterns over a variety of climatic and site conditions. Sites should be selected to represent the categories or types of facilities required and/or constructed based on permit

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[2] Management measures may include BMPs or other facilities, locations of floodplain or stream restoration, or alternative land use practices designed to mitigate the effects of hydromodification.

requirements and watershed plans. These categories should include both site-based and regional facilities and those with different design goals (e.g. flow-duration control, retention/infiltration, capture/use, sediment management).

3.1.2 Sampling Season, Frequency, and Duration

Performance monitoring should occur during the storm season because most hydromodification BMPs are designed to help manage stormwater runoff. It is preferable to have continuous flow monitoring occur throughout the storm season for several years following installation in order to provide robust information on representative BMP performance. If this is not possible, at least three storms should be monitored per season. Continuous flow measurements should be initiated at the start of each monitored storm event and continue until all retained water has been discharged from the facility or infiltrated. A subset of representative BMPs and reference sites should be monitored annually to assess performance relative to design specifications.

3.1.3 Specific Sampling Triggers

Monitoring should be initiated based on two triggers. First, each new facility that is not already included in the set of representative BMPs should be monitored. The immediate downstream areas should also be monitored (for representative BMPs). Second, monitoring intensity should be increased following major storm events that may influence BMP performance. If the preferred continuous flow monitoring approach is used, it will provide information over a range of conditions representing seasonal and episodic variability, eliminating the need to increase monitoring intensity following large storms.

3.2 Question #2

What factors influence the efficacy of hydromodification management strategies?

Improved management over time comes from an understanding of the factors that affect the effectiveness of various management actions. Information gained from other monitoring can only be interpreted through such an understanding. Therefore, such “causal evaluation” is an integral part of a comprehensive monitoring program. Evaluation of factors that affect performance is best done through a GIS-based landscape assessment, supported by targeted field evaluation of potential stressors (or pressure indicators). In practice, the outcome of Questions #2 and #3 should be used together to support causal assessment that informs management decisions. This assessment should use much of the same information compiled as part of the watershed analysis that forms the foundation of the overall monitoring program. GIS indicators should be supplemented by field documentation of stressors observed during monitoring activities associated with the other management questions. In particular the CRAM stressor checklist, PHAB, and flow data can provide field-derived insight into the causes of decline or recovery of a particular stream reach.

3.2.1 Design and Location Criteria

Causal assessment is not monitoring in the true sense, but occurs through targeted assessment of potential causes of failure or factors that contribute to success. This evaluation should occur at the watershed scale and consider all upstream and downstream contributing factors. The watershed analysis that forms the foundation of the integrated monitoring program can form the basis of this assessment. In addition, causal evaluation frameworks such as the USEPA Causal Analysis/Diagnosis Decision Information System (CADDIS, http://www.epa.gov/caddis/index.html) can be used to evaluate past data sets and provide insight into causes of management measure effectiveness. Results of the watershed-scale analysis may suggest targeted locations for more detailed investigations where field based measures can be used to support the causal evaluation.

3.2.2 Sampling Season, Frequency, and Duration

Because this question is answered mainly through GIS analysis it can occur in ongoing and as-needed manner. As results are obtained from the other monitoring questions, this analysis should be updated and revised to improve understanding of causes of success and failure.

3.2.3 Specific Sampling Triggers

As with other questions, the analysis of causation should be intensified following substantial changes in land use practices or following installation of new management measures. Unlike other questions, natural catastrophic events such as fires and floods would not necessarily trigger intensified causal assessment. Additional field assessment should be triggered if performance monitoring under Question #1 reveals that individual (or groups) of BMPs are not functioning as intended.

Effectiveness Assessment (Local Agency/Permittee Directed)

3.3 Question #3

How effective are specific management strategies at protecting the physical and biological integrity of streams from the effects of hydromodification?

The efficacy of management measures is a function of BMP performance (Question #1) and the effect of those management actions on instream conditions (Question #3). A combination of physical and biological measures taken at channel cross-sections downstream of the BMPs can be used to evaluate effectiveness (Table 5). These measures can be evaluated against comparable assessment conducted prior to the BMP being installed and to unimpacted reference locations[3]. Results from this question should be used to adapt and improve management practices over time in order to inform future

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[3] In some watersheds, it may be difficult to find unimpacted reference sites. In this situation regional reference sites may be used (hence the importance of maintaining reference networks). Pre-project data is especially important when reference sites are difficult to locate.

decisions about the design and placement of BMPs. This is a core element of adaptive management and will hopefully increase ability to protect and restore stream channels into the future.

Table 5. Field indicators for measuring effectiveness of hydromodification management.

Geomorphic Indicators	Biologic Indicators
Bed material composition	Benthic macroinvertebrates
Armoring potential	Stream algae
Grade control	California Rapid Assessment Method
Incision/downcutting risk	
Probability of mass wasting	
Evidence of fluvial erosion	
Consolidation of bank material	
Channel width:valley width	
Channel Evolution Model class	
Channel geometry	
Physical Habitat Assessment (PHAB)	

In addition, as stated above, long-term continuous flow data will be valuable in assessment of BMP effectiveness.

3.3.1 Design and Location Criteria

A before-after-control-impact (BACI) design (Stewart-Oaten et al. 1986) is recommended for assessing hydromodification management effectiveness. Targeted stream reaches downstream of BMP locations should be sampled prior to and after BMP installation/construction (at least 2 seasons of pre-BMP sampling are recommended). The condition of the stream channel receiving the BMP discharge should be considered when deciding where to monitor effectiveness. For example, BMPs that discharge into engineered channels or streams subject to a variety of other stressors may not be appropriate for effectiveness monitoring. Instead, effectiveness monitoring should be prioritized in areas where BMPs discharge to soft-bottom channels where the influence of other stressors is relatively minimal.

If possible, a set of reference sites should also be selected that receive runoff from relatively natural landscapes. The paired design increases statistical power to detect differences associated with management actions from natural variability associated with seasonal and decadal scale climate patterns. Because different channel types will respond differently, different channel susceptibility classes should be included for reference sites and streams downstream of BMPs (i.e. high, medium, low according the screening tool developed by Bledsoe et al. 2010). If possible to obtain, three replicate reference sites should be included for each major channel category. Reference sites are also an important component of trends monitoring (see Question #5). Therefore, to the extent possible, these sites should have ownership and access conducive to long-term ongoing monitoring.

3.3.2 Sampling Season, Frequency, and Duration

Instream conditions can be evaluated during the dry season when appropriate to sample biological indicators. Channel cross-sections should be taken at least annually for the first five years following BMP installation/construction (frequency may increase following catastrophic events, see below). If possible, continuous flow monitoring stations should be installed in order to accurately capture hydrograph shapes even in small, flashy basins. Following the initial monitoring period a subset of representative sites (and reference sites) should be monitored annually as part of long-term (decadal) regional monitoring programs. Long term monitoring is important as there may be a substantial lag time between land use changes and/or initial management actions and stream responses.

3.3.3 Specific Sampling Triggers

Monitoring should be initiated based on two triggers. First, construction of each new representative BMP should initiate monitoring of that BMP (Question #1) and the immediate downstream area (in addition, to the recommended pre-construction monitoring) – for a representative set of sites. Second, monitoring intensity should be increased following major storm events or fires. Following these events, sites should be monitored more frequently within a storm season (i.e. number of storms per year should increase) for the first three years following the catastrophic event. The need for continuing high intensity monitoring beyond this time period should be evaluated based on the results from the first three years.

Spatial and Temporal Trends Assessment (Cooperative Statewide or Regional Monitoring)

Questions #4 and #5 can only be answered through long-term coordinated monitoring that crosses jurisdictional boundaries. Therefore, these questions should be addressed through cooperative programs at the state or regional level (e.g. southern California) that is coordinated by appropriate state or regional agencies. It is recommended that a pilot project focusing on Questions #4 and #5 be conducted first prior to implementation on a larger scale

3.4 Question #4

What is the spatial footprint of hydromodification responses relative to discharge locations?

Hydromodification effects have the potential to propagate upstream or downstream from a discharge location. Therefore, assessing the success of management measures requires an evaluation of the spatial extent of effects. This is best accomplished through a long-term regional monitoring program. Spatial effects are monitored during the dry season at a series of targeted location along a stream corridor. Measures include channel cross-sections and the same physical and biological indicators used to evaluate effectiveness (Question #3, see Table 3). In some cases the same sites may be used to answer spatial extent and effectiveness questions. Results from this question should be used in combination with the results of trends monitoring (Question #5) and compared to the causal factors evaluated under Question #2. These comparisons will allow a more robust analysis of the effect of management actions.

3.4.1 Design and Location Criteria

Question #4 is best addressed through targeted sampling. Spatial effects should be evaluated upstream and downstream of the same set of management areas or BMPs monitored for Question #1, if suitable areas exist[4]. Monitoring sites should be channels with unarmored bed and banks that would be subject to potential effects of hydromodification. In general, the "analysis domain" should be consistent with and extend slightly downstream of the limits suggested by the Hydromodification Screening Tool (Bledsoe et al. 2010). In brief, the analysis domain proposed by Bledsoe et al. (2010) for downstream monitoring should occur to the first location that meets on of the following criteria:

- at least one reach downstream of the first grade-control point (but preferably the second downstream grade-control location)
- tidal backwater/lentic waterbody
- equal order tributary (Strahler 1952)
- a 2-fold increase in drainage area

Upstream monitoring should extend for a distance equal to 20 channel widths OR to grade control in good condition – whichever comes first. Within that reach, identify hard points that could check headward migration, evidence that head cutting is active or could propagate unchecked upstream. As with Question #3, different channel types are expected to respond differently. Therefore, ideally 3-5 sites representing high, medium, and low susceptibility (per Bledsoe et al. 2010) should be monitoring for each category of management action. Priority should be given to high and medium susceptibility sites, if resources pose a constraint. Sites should be conducive to long-term monitoring in terms of logistics and access.

3.4.2 Sampling Season, Frequency, and Duration

Sampling consists of the same physical and biological indicators measured for Question #3. Therefore, sampling should occur during the spring sampling season during the index period for benthic invertebrate and algal sampling protocols (typically April – June depending on weather conditions). Because sites used to answer this question are intended to be monitored over extended periods of time, sampling every other year is typically sufficient (subject to the triggers described below). Furthermore, as described below the downstream extent may need to change over time based on monitoring results. Many monitoring programs re-evaluate the general monitoring design at a regular interval, typically every five years, and make adjustments to accommodate evolving management needs.

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[4] It may also be desirable to select several legacy BMPs from other parts of the watershed to include in this element of the monitoring program.

3.4.3 Specific Sampling Triggers

Monitoring should be initiated based on the same triggers used for Question #3. First, construction or installation of a new representative BMP should initiate monitoring of that BMP (Question #1) and the immediate downstream area (Question #3). State and local agencies should coordinate to identify representative BMPs for monitoring. Second, monitoring intensity should be increased following major storm events or fires. Following these events, sites should be monitored more frequently for the first three years following the major event. The need for continuing high intensity monitoring beyond this time period should be evaluated based on the results from the first three years.

Spatial extent monitoring should also include an adaptive element. If effects are consistently observed downstream of BMPs or other management measures over several years, the monitoring location should be extended further downstream. This will allow incremental improvement in the ability to determine the actual extent of potential downstream effects. Note that this should include consideration of how past influences (e.g., headcutting from historical, pre-urban impacts) may interact with contemporary influences

3.5 Question #5

How do responses to hydromodification management vary over time?

Trend monitoring is particularly important for understanding hydromodification effects given that stream channel response is often stochastic/episodic and may occur suddenly following certain size storms or under specific combinations of circumstances. Conversely, gradual effects may persist for decades and stabilization and recovery following restoration and management may be manifested over long periods of time. Monitoring sentinel sites over long periods of time is the best way to understand these long-term effects and trajectories and to develop data sets with sufficient statistical power to detect change. Most of the monitoring should occur during the dry season and should include channel cross-sections the same physical and biological indicators used to evaluate effectiveness (Question #3, see Table 3). In addition, continuous flow monitoring through wet and dry seasons at key locations is necessary to understand effect of management measure over time. Trends monitoring is best accomplished through a long-term regional monitoring program. In some cases the same sites may be used to answer trends and effectiveness questions.

3.5.1 Design and Location Criteria

Trend monitoring should occur at two types of targeted sites. First, sentinel sites should be established at key watershed locations in consideration of past and current land use practices. These may also include locations downstream of important long-term management areas, such as regional retention basins or large floodplain restoration projects. They may also be at locations that integrate portions of the larger watershed (e.g. major tributary confluences). When choosing sites near confluences, care should be taken to not establish the monitoring site at the confluence, but just upstream of the confluence. This will reduce potential confounding factors associated with dynamism that often occurs when two different size catchments join. Second, reference sites should be monitored to help document a baseline range of variability in response to normal decadal scale weather patterns. These natural adjustments will help bound the range of expected responses at sites subject to management measures. As with Questions #3 and #5, different channel types are expected to respond differently. Therefore, ideally 3-5 sites representing high, medium, and low susceptibility (per Bledsoe et al. 2010) should be represented in both the sentinel and reference sites. Priority should be given to high and medium susceptibility sites if funding poses a constraint. All trend sites should be amenable to long-term monitoring in terms of access and logistics.

3.5.2 Sampling Season, Frequency, and Duration

Trend monitoring should occur during both the wet and dry seasons. Dry season sampling consists of the same physical and biological indicators measured for Question #3. Therefore, sampling should occur during the spring sampling season during the index period for benthic invertebrate and algal sampling protocols (typically April – June depending on weather conditions)[5]. Wet season sampling consists of continuous flow monitoring and channel cross-section analysis. If continuous flow monitoring is not possible, event-based flow monitoring should occur during one of the three storm events monitored for Question #1, preferably an early season storm of moderate intensity. Discharge measurements should be initiated at the start of each monitored storm event and continue until flow has receded to at least 50% of peak flow. Continuous flow monitoring at 15-minute intervals is preferred, if possible. Channel cross-section and longitudinal profile should be surveyed immediately following the end of each monitored storm event. Ideally, sampling would occur at least every other year on an ongoing basis. Many monitoring programs re-evaluate the general monitoring design at a regular interval, typically every five years, and make adjustments to accommodate evolving management needs.

3.5.3 Specific Sampling Triggers

Trend monitoring should occur annually at the targeted reference and effects sites. If natural or anthropogenic factors cause a trend site to no longer be suitable for monitoring, it should be replaced with a comparable site. Monitoring intensity should be increased following major storm events or fires. Following these events, sites should be monitored more frequently for the first three years following the catastrophic event. The need for continuing high intensity monitoring beyond this time period should be evaluated based on the results from the first three years.

Ambient Condition Monitoring (Cooperative Statewide or Regional Monitoring)

3.6 Question #6

What is the physical and biological condition of streams relative to established regulatory or management objectives?

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[5] Many suitable sites for hydromodification monitoring will be dry for most of the year. These sites may be not be amenable to benthic macroinvertebrate or algae sampling.

This question provides an estimate of the regional extent and range of hydromodification effects through an ambient assessment of physical and biological conditions within the stream. This information provides context for interpreting the results of all other monitoring questions. Results from ambient condition monitoring document the range of expected conditions and provide insight into how those conditions vary across physical gradients such as slope, geologic setting, and watershed position. Monitoring should occur during the dry seasons and should include channel cross-sections and the same physical and biological indicators used to evaluate effectiveness and trends (Questions #3 to#5, see Table 3). Where possible, long-term continuous flow monitoring should also be used to help answer this question. Results from targeted monitoring from subsequent questions can be compared to the ranges produced by this question.

3.6.1 Design and Location Criteria

The characterization question is best answered through a probabilistic design. Probabilistic design allows for statistical inference of overall condition in the monitoring area based on sampling at a relatively small set of randomly selected locations. Sites can be stratified by watershed or other management unit of interest or can sampled as a single stratum and then grouped later for comparative analysis. As a general rule, approximately 30 sites should be sampled per stratum to provide a statistically meaningful estimate of overall condition within the monitoring area. In southern California, the Stormwater Monitoring Coalition (SMC) has a regional monitoring program covering the region from Ventura through San Diego counties that has produced a set of randomly selected sites. The SMC sites could also serve as locations for assessing the regional extent of hydromodification effects.

3.6.2 Sampling Season, Frequency, and Duration

Ambient condition assessment should occur during the spring sampling season during the index period for benthic invertebrate and algal sampling protocols (typically April – June depending on weather conditions). Sampling should occur annually on an ongoing basis. Many monitoring programs re-evaluate the general monitoring design at a regular interval, typically every five years, and make adjustments to accommodate evolving management needs. The current SMC regional monitoring design involves sampling a different set of probabilistic sites each season. This design typically provides the most robust assessment of regional condition. However, revisiting a portion of previously sampled sites can provide information to support trends assessment (see Question #5).

3.6.3 Specific Sampling Triggers

Ambient monitoring typically involves sampling a specific number of sites each year irrespective of environmental conditions. However, intensified sampling may be desirable if substantial changes to the condition of a specific area are expected in association with a natural event (e.g. large flood or fire) or land use change (e.g. large new development area, major stormwater basin). Under these circumstances additional probabilistic sites can be selected from the regional sample draw and monitoring for a discrete period of time. This will help determine if there is a change in ambient condition in the specific area of interest.

3.7 Summary of Monitoring Locations

A hypothetical layout for all elements of this monitoring plan is shown in Figure 5 (note that the number of sites shown are for illustrative purposes only and not meant to imply an actual program). As stated above, this plan can be implemented modularly based on needs and not all elements would need to be implemented together (i.e. use as a toolbox of approaches). The first two elements (performance and effectiveness monitoring) will typically be implemented by permittees as part of their monitoring requirements. The second two elements (trends and characterization monitoring) are best done through long-term cooperative regional monitoring. However, all monitoring elements should be closely coordinated, particularly because individual sites may serve multiple roles (e.g. a site used for tends assessment may also be a reference site or an upstream BMP site). Also, a subset of sites initially used for permittee-directed monitoring may ultimately be incorporated into regional monitoring programs. Where possible, sites (or data) from other monitoring programs may be used to also support hydromodification monitoring.

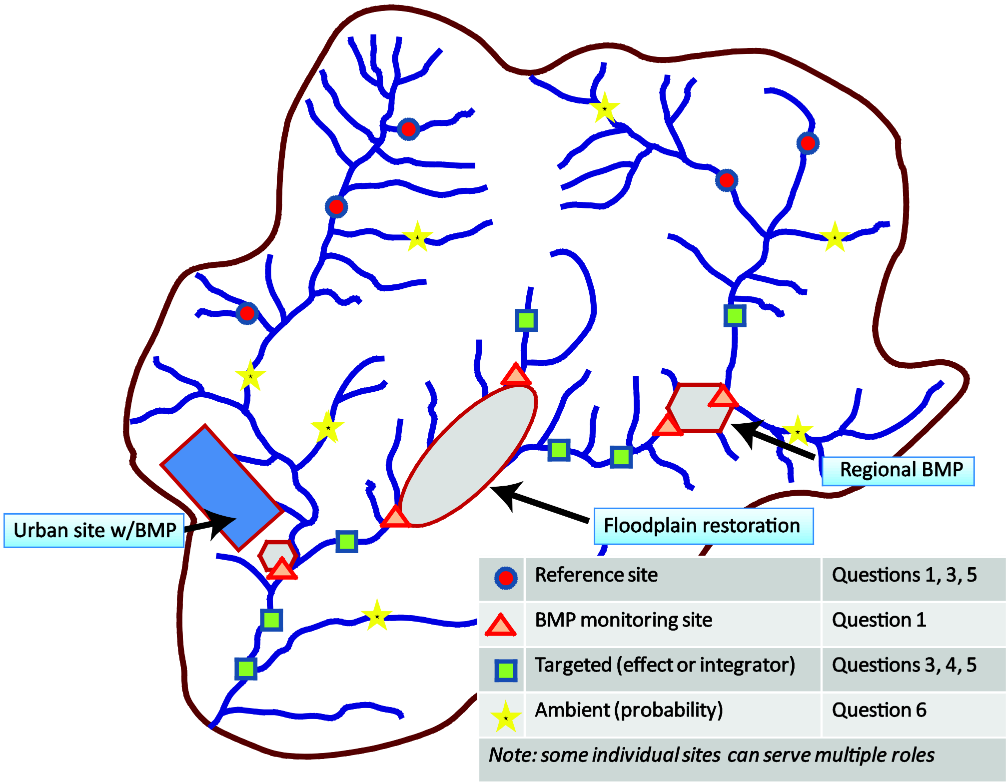

Figure 5. Hypothetical summary of how monitoring site might appear in a watershed. The number and locations of sites is for illustrative purposes only and are not meant to represent an actual program.

3.8 Preliminary Cost Estimates

Implementation of the recommended monitoring elements will require both up-front commitment of resources and recurring annual expenditures. Table 6 provides estimated unit costs per site for the major recommended field indicators.

Table 6. Unit costs for one-time up front and recurring annual monitoring of major indicators.

One time, up front costs		**Recurring Annual Costs**	
Flow		**Flow**	
pressure trandcers	$1,250	annual data download/processing	***$5,000***
station set up	$1,000		
Total	***$2,250***	**Biology and Geomorphology**	
Biology and Geomorphology		Field geomorphic assessment	$2,000
site recon & selection	*$2,000*	field collection of inverts and algae	$2,000
access and permits	$1,000	CRAM	$1,000
Total	***$3,000***	benthic inverts taxonomy	$600
		diatoms taxonomy	$400
		data entry, QA/QC	$500
		Total	***$6,500***

We estimate the up-front per site cost to be $5,250 and annual recurring per site cost to be $11,500. Based on general recommendations in this chapter we also provide a range of estimates for annual monitoring costs for each type of monitoring site and each major indicator (Table 7). If all monitoring elements were implemented, the annual cost would range from $456,000 - $569,500 per watershed management area, depending on the number of sites sampled each year. However, $195,000 of that cost would be for ambient condition assessment at probabilistic sites. The overall costs do not include monitoring infrastructure, such as data management, training, and reporting. As stated above, the intent is not for all elements to be implemented concurrently or by the same entity. Rather, we anticipate that various elements would be implemented over time by a combination of local and regional partners in order to defray costs and make implantation more practical. The costs provided in Table 7 should be considered preliminary estimates only.

Table 7. Preliminary cost estimates for each type of site and indicator representing the major monitoring elements.

			Flow		Biology and Geomorphology	
Type of Site	Monitoring Questions	No. of sites	up-front one-time	recurring annual cost	site recon: up-front, one time cost	recurring annual cost
BMP monitoring sites	1	6 - 9	$13,500 - $20,250	$30,000 - $45,000		
BMP reference sites (sites w/o BMPs)	1	3 - 5	$6,750 - $11,250	$15,000 - $25,000		
Instream effectiveness monitoring sites	3	6 - 9			$18,000 -$27,000	$39,000 - $58,500
Spatial effects sites	4	12 - 15			existing locations	$78,000 - $97,500
Trends sites	5	6 - 9	$13,500 - $20,250	$30,000 - $45,000	use existing effectiveness sites	
Reference sites	3, 4, 5, 6	6 -9	$13,500 - $20,250	$30,000 - $45,000	$18,000 -$27,000	$39,000 - $58,500
Probalisitic sites	6	30			$90,000	$195,000

4.0 USE OF MONITORING RESULTS TO SUPPORT DECISIONS

Monitoring should not be a static endeavor. In addition to answering the core monitoring questions, information compiled through the monitoring programs should be used to inform management decisions and to guide evolution of the monitoring program itself. Results of the monitoring program should be added to the original watershed analysis and used to support issues such as:

- Identifying successful management measures that should be replicated in other areas and unsuccessful measures that should be modified or abandoned.
- Identifying areas of the watershed in need of additional management attention
- Conducting statistical power analysis to refine the location and frequency of monitoring and to improve protocols
- Providing data to refine, calibrate, and validate watershed models
- Improving understanding of the stress-response relationships between flow, physical habitat, and biological communities in order to support the evaluation of potential causes of degradation.

Full benefits of monitoring accrue based on a commitment to long-term implementation, which requires decision support systems and infrastructure to support the monitoring program. The resources necessary to support long-term ongoing monitoring will be beyond the means of individual municipalities or permittees. A long-term commitment to hydromodification monitoring can be best accomplished through a long-term regional grant program. Long-term implementation needs can be most effectively met through coordination with existing monitoring programs and by sharing existing monitoring infrastructure.

4.1 Triggers for Management Actions

Monitoring results should not only assess performance/compliance, but should inform adaptive management decisions. Hydromodification management is an immature field relative to other forms of water quality management. Consequently, there are relatively high levels of uncertainty associated with long-term effects of management actions.

Triggers for specific management actions will need to be developed for each watershed program consistent with the goals, objectives, and regulatory requirements of that program. These triggers can be informed by many factors, such as:

- Established regulatory limits (e.g. deviation from an objective, change in bioassessment score
- Differences from reference conditions
- Deviations from pre-project conditions
- Deviations from a specified percentile of ambient conditions

Management actions may be informed by results of effectiveness or condition monitoring. Results of the effectiveness monitoring (Question #3) can trigger changes in the design of facilities or restoration areas (i.e. retrofits) or changes in operation (e.g. frequency of basin clean outs, elevation or size of discharge outlets). For example, a magnitude or duration of outflow from a basin of more than 15% greater than the designed specification could trigger specified management actions. Results from condition monitoring (Questions #4 and #5) can also trigger actions, such as additional causal assessment or implementation of contingency management measures (e.g. additional floodplain restoration). For example, an increase in channel cross sectional area of 15% greater than reference conditions could trigger the need for additional upstream restoration. Similarly, IBI scores consistently below a specific level could trigger the need to initiate a formal causal assessment. However, it is important to note that several watershed stressors may be contributing to the response observed during monitoring. The combined effects of hydromodification along with other stressors should be accounted for during the causal assessment.

Along with adaptation of management actions, monitoring results should also inform evolution of the monitoring program itself. Such “adaptive management” requires long-term commitment to the program; consequently, cooperation with ongoing regional monitoring programs become more critical. As the hypothesis underlying the monitoring program are supported or refuted, the design, location, frequency and/or choice of indicators should be adjusted. Results of early monitoring should inform refinements of subsequent years monitoring. For example, information on how far downstream hydromodification effects propagate (Question #4) can result in changes to the spatial extent of monitoring. Information on the rate of channel evolution (Question #5) can result in a change in the frequency of monitoring or adjustment of the triggers for intensified monitoring. Finally, increased knowledge on the sensitivity of specific indicators at detecting changes may result in some indicators being dropped and new indicators being added, or change in the overall intensity of monitoring.

4.2 Data Management, Information Dissemination, and Reporting

Realization of the goals of any monitoring program to inform management actions depends on an effect data management program. This is particularly important for watershed based monitoring program where information will need to be shared across jurisdictions. Monitoring programs should take advantage of regional data management systems, such as the California Environmental Data Exchange Network (CEDEN; http://www.ceden.org) and its associated Regional Data Centers. This requires up-front development of standard data formats that can be shared across programs. The Regional Data Centers provide secure web-based portals through which data can be accessed in a variety of ways. The goal is to provide an easy mechanism for retrieving monitoring results so that they can be used to inform management decisions.

Regular reporting should be directly related to the monitoring questions. Synthesis and analysis should be designed to clearly answer the questions and hypothesis in a way that informs decisions. If management triggers have been developed, data summaries should directly relate to whether triggers have been surpassed. Furthermore, monitoring results should be made readily available to decision makers and the public as a means of education and to show the outcomes of the investment of resources toward addressing hydromodification.

4.3 Quality Assurance

Confidence in monitoring data requires standardized procedures for sample collection, processing, analysis, and data reporting. These procedures must be established up-front and clearly communicated through the various data and information management systems (see above). Quality assurance procedures are necessary for managers to have confidence in the quality of the data used to support their decisions. Data Quality Objectives (DQOs) are quantitative and qualitative statements that clarify study objectives, and specify the tolerable levels of potential errors in the data. DQOs are generally used to determine the level of error considered to be acceptable in the data produced by the monitoring program.

Ongoing training and field audits of monitoring sites should also be included as part of the quality assurance program. These actions will help ensure consistency and accuracy in data collection, which will be essential to the ability to synthesize data over time and space.

4.4 Final Considerations

This monitoring program includes aspects that are different than what is typically included in existing water quality monitoring. Monitoring methods, approach and program management will require developing new skills and capacities at the local and regional level. In addition, logistical challenges such as identifying sufficient, appropriate monitoring sites, securing site access, data management, and training of field staff will need to be addressed. We recommend that several pilot demonstration projects be conducted in order to provide an opportunity to refine the recommendations provided in this document and develop examples of program implementation. These early efforts will provide important lessons and templates that can be used to aid in long-term broad implementation. From the regulatory perspective, new frameworks may need to be developed to accommodate adaptive management and to encourage and facilitate integrated, watershed and regional scale solutions to hydromodification monitoring and assessment.

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APPENDIX A: BIBLIOGRAPHY OF SOURCE INFORMATION ON STREAMFLOW MEASUREMENT

Flow measurement is a key component of hydromodification monitoring. Long-term continuous flow monitoring provides much more robust data for general evaluation, assessment of management measure effectiveness and model calibration or validation. Although, less desirable, regular manual measurements of flow also provide important data for understanding behavior and response of stream channels.

There are many different approaches to measuring streamflow ranging from direct measures of velocity and cross-sectional area to relatively inexpensive approaches that measures stage (i.e. height of the water surface) and translate that to discharge using an established relationship based on channel geometry. The accuracy of the measurement is affected by the specific approach, the complexity of the technique and practitioner performance. The references below provide background information on various approaches, limitations and considerations for use, and description of protocols.

Rantz, S.E., et al. (1982). *Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge.* United States Geological Survey Water-Supply Paper 2175. Washington D.C.

This report is a training and operations manual for USGS technicians that describes gaging station installation, and measurement of stage and discharge. It provides guidance on selecting a site for a gaging station, including considerations of channel geomorphology that come into play. Fundamentals of stage measurement are discussed and various methods used in recording and non-recording stream gaging stations are described. The report also discusses the fundamentals and theory of several methods of stream discharge measurement techniques, provides a practical description of the procedures and equipment used, and describes technical issues associated with each. There is also a discussion of the indirect determination of peak discharge.

Rantz, S.E., et al. (1982) *Measurement and Computation of Streamflow: Volume 2. Computation of Discharge.* United States Geological Survey Water-Supply Paper 2175. Washington D.C.

This report is a training and operations manual for USGS engineers to process field measurements into relationships of stage and discharge, to compute daily-discharge records, and to create a graphical representation of the stage and discharge relationship. It covers in detail the computation of stage-storage relationships for various gaging station equipment configurations and provides detailed procedural guidance for documenting, reporting, presenting and publishing gaging station records and computed stage-discharge relationships.

Various downstream natural hydraulic controls and various man-made controls of known geometry are discussed with respect to their effects on stage and discharge relationships. The report covers in depth the topic of determining, analyzing, and correcting for various causes of shift in the stage-storage relationship due to changes in various man-made and natural stream controls, and due to ice effects. It also discusses some typical causes of shift seen in the stage-discharge relationship in sand-channel streams relative to fixed channels, and methods for troubleshooting and properly charting and adjusting the rating curve. Methods for extrapolation of stage-discharge relationships beyond measured data both on the low and high ends of the flow spectrum are reviewed.

The report contains a discussion of the theory and provides several methods for determining discharge ratings for tidal streams and other instances of variable backwater, or discharge--such as at hydraulic facilities--which may require extra parameters such as slope and velocity index. Additionally, it presents examples for establishing the relationships, with further discussion of the theory and methods for adjusting unsteady flow rating curves to represent steady flow conditions.

Freeman, Lawrence A. et al. (2004). ***Use of Submersible Pressure Transducers in Water-Resources Investigations*****. United States Geological Survey Techniques of Water-Resources Investigations 08-A3: Reston, VA.**

Pressure transducers are commonly used to measure water surface elevation in stream gaging. This report presents the theory behind data collection using pressure transducers, particularly in well-type installations. The report describes the fundamentals of data collection protocol, and provides guidance on various field methods for installation, data processing (refining and calibrating), and quality assurance of collected data. There is a discussion of the physics and electronic circuitry behind pressure transducer operation, as well as the errors inherent in the system. Examples of application in various environments are discussed, along with typical related operational difficulties and potential solutions.

Mueller, David S. and Wagner, Chad R. (2009). ***Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat.*** **United States Geological Survey Techniques and Methods 03-A22. Reston, VA.**

This report explains in detail the procedures for measuring discharge using an Acoustic Doppler Current Profiler (ADCP). It provides procedures for equipment preparation, field methods and equipment configurations for data collection, and data management and processing, including quality control. The report discusses the theory behind ADCP measurement technology, including potential limitations. It relates this discussion to practical use, providing procedures for equipment calibrations and maintenance adjustments to address various performance issues.