O-6.3 HYDROLOGY/STORMWATER

Comment Letter O-6.3

EXHIBIT 3

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Dear Mr. Silver:

As you requested, I reviewed documents submitted by the proponent of the Otay Ranch Village 14 and Planning Areas 16/19 development (Otay Ranch, the development, or the project) in San Diego County (the County). I focused primarily on the proposed stormwater management system and the project's potential effects on the waters that would regularly receive its stormwater runoff (Jamul Creek, Upper Otay Reservoir, Lower Otay Reservoir, and Proctor Valley Creek). I also include the Otay River, San Diego Bay, and the Pacific Ocean downstream even though the Lower Otay Reservoir does not discharge often, because a discharge is very likely the result of a large storm with high pollutant transport potential. This letter presents the conclusions I reached.

In forming these conclusions I reviewed and assessed a number of sections of the Draft Environmental Impact Report (DEIR), concentrating particularly on sections 3.1.2 (Hydrology and Water Quality) and 2.6 (Geology and Soils) and Appendices 3.1.2-2 (Major Stormwater Management Plan, with Attachments 1a-d), and 3.1.2-4 (Hydromodification Flow Control Study). I also referenced: (1) DEIR Chapter 1 (Project Description, Location, and Environmental Setting); (2) the County of San Diego's BMP Design Manual (2016); and (3) sources from the literature of the stormwater management field cited in footnotes. O-6.3-1

In evaluating the Otay Ranch documents I applied the experience of my 41 years of work in the stormwater management field and 11 additional years of engineering practice. During this period I have performed research, taught, and offered consulting services on all aspects of the subject, including investigating the sources of pollutants and other causes of aquatic ecological damage, impacts on organisms in waters receiving urban stormwater drainage, and the full range of methods of avoiding or reducing these impacts. Attachment A to this letter presents a more complete description of my background and experience, and Attachment B contains my full *curriculum vitae*.

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SUMMARY OF CONCLUSIONS

A project put forward for approval to proceed should collect all underlying data pertinent to the required environmental assessments, conduct those assessments with the best available methods, and provide all of the information regulators and citizens need to make a full and confident evaluation of the proposal and its potential environmental effects. The Otay Ranch project documents do not meet this standard, specifically with respect to:

- Not performing sufficient topographic analyses in a setting of very steep terrain;
- Not obtaining adequate soils data through on-site testing and analysis;
- As a consequence, compromising a key analytical task, properly assessing construction-phase erosion potential and the consequent management strategies needed to prevent negative impacts to the receiving waters;
- Not preparing anything close to a complete construction-phase stormwater pollution prevention plan, a necessity before regulatory decision making because of the steep slopes to be developed and sensitivity of the receiving waters to the pollutants potentially released from a poorly controlled construction site;
- As a further consequence of insufficient topographic analyses, failing to adequately assess the conveyance of stormwater runoff on steep flow paths and its potential erosiveness; O-6.3-2
- As a further consequence of inadequate soils data, running hydrologic models underlying hydromodification and water quality control with input parameters that may or may not be valid;
- Not examining common and significant domestic sources of stormwater pollution and the source controls that should be well developed to address them;
- Proposing a treatment system that I project will remove no more than approximately half of the entering loading of any pollutant, less than that in some cases, and actually will produce more phosphorus in the outflow than it receives;
- Not recognizing that the shortcomings of construction-phase and permanent stormwater management evident in the DEIR pose major potential problems for the downstream receiving waters; and
- Particularly, ignoring the greatest potential problem, increased phosphorus transport after development and its ability to advance eutrophication in the Upper and Lower Otay Reservoirs, a condition with many serious implications for water quality in the reservoirs,

operations of the City of San Diego's drinking water treatment plant, and the consumers of the plant's product. O-6.3-2 Cont.

These flaws in the DEIR render its judgments of impact non-significance not to be well founded for the affected receiving waters. The remainder of my letter elaborates on these points. O-6.3-3

DEFICIENCIES IN ASSESSMENT METHODS

The DEIR is compromised by defects in certain methods used in the analyses underlying its conclusions and proposals, specifically in topographic analyses and accounting for soils conditions. The shortcoming in topographic analysis in such extremely steep territory as the Otay Ranch site has implications for constructability, particularly in relation to construction-phase stormwater management, and for conveyance of stormwater runoff within and away from the finished development. Lacking sufficient definition of the soils on-site affects planning for construction-phase stormwater management and compromises the modeling performed to analyze post-construction hydromodification and runoff water quality treatment. O-6.3-4

Topographic Analysis

The DEIR is strangely reticent on the matter of topographic slope, given that the proposed development is to occur in a location shown on the topographic map for the Jamul Mountains area[1] as exceedingly steep ground. The Steep Slopes Analysis maps in DEIR Chapter 1 show the Village 14 and Planning Area 16 on-site and off-site development sites to have 20-30 percent of the areas exceeding 25 percent slopes. While the chapter states that there is a standard that requires preservation of at least 83 percent of slopes with gradients of 25 percent or greater, that provision still leaves substantial disturbance of very steep areas. Typically in these circumstances the project proponent would forthrightly define topographic conditions in a quantitative, subarea-by-subarea fashion in both existing and final configurations. To comply with this practice, the DEIR should lay out for each unit the area encompassed, slope range (*e.g.*, 15-25 percent), land cover, and drainage pathways in the pre-and post-development states. The document does nothing of this nature. O-6.3-5

If fully described in this way, a reader of the DEIR could see where the major challenges would lie during construction (the steepest areas experiencing clearing), the approximate quantities of grading required at those locations, and the implications of conveying runoff water away from different parts of the site in the temporary construction and permanent conditions. The proponent should apply this information in analyses aimed at putting forth specific measures to avoid problems. Without fully describing the steepness of the slopes that the project would disturb (e.g. where 30-40 percent slopes are located) it is impossible to accurately forecast the potential runoff and pollutant transport from the project. I expand on this issue below for the construction and finished phases.

[1] http://www.efghmaps.com/SAN_DIEGO/JAMUL_MOUNTAINS.GIF.

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Soils Definition

Soils characterization in the DEIR work relied solely on the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) soil survey. Soil survey data of this nature were generally not obtained through on-site testing, or even observation, but commonly through more remote sensing. They are, accordingly, sometimes wrong or misleading. Soils and related hydrogeologic conditions can vary extensively within short distances. Coarser, more infiltrative formations can lie among finer, more restrictive ones, to the detriment of localizing hydrologic analyses to get the most accurate estimates of runoff production. Likewise, relatively more erosive formations can be interspersed with more resistant ones; not knowing conditions locally around the site is a disadvantage to proper construction-phase stormwater control assessment. O-6.3-6

Soil conditions are highly important in hydrologic modeling and stormwater practice selection and design. It is essential for the proponent to characterize thoroughly the soils of all portions of the site that will be subject to construction. This characterization should include areally extensive soil coring to some depth below the surface and analysis of textural properties in the core samples. The resulting data should be employed in reassessing the selection of practices and their placement and design, both in the construction and post-construction phases.

This position agrees with the San Diego County BMP Design Manual (County Manual), where Table D.3-1[2] notes that regional soil maps are known to contain inaccuracies at the scale of typical development sites. Furthermore, the County Manual advocates, for the planning level, confirmation of mapped soil types with site observations. For the design phase, it does not consider NRCS soil survey maps to be suitable at all, unless a strong correlation is developed between soil types and infiltration rates in the direct vicinity of the site and an elevated factor of safety is used. O-6.3-7

Similarly, a USEPA-sponsored report[3] states, "Very large errors in soil infiltration rates can easily be made if published soil maps … are used … it is recommended that site specific data be obtained."

Important considerations in gathering site-specific soils data are, How many spots should be tested, and how should they be distributed? A NRCS publication[4] advises:

> It is recommended that a minimum of three samples or measurements be collected on any one soil type and management combination. In general, the greater the variability of the field, more measurements is needed to get a representative value at the field scale.

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[2] County of San Diego. 2016. County of San Diego BMP Design Manual, Appendix D, Approved Infiltration Rate Assessment Methods for Selection of Storm Water BMPs (page D-3). County of San Diego, San Diego, CA. Attachment C.

[3] Pitt, R., J, Lantrip, R. Harrison, C.L. Henry, and D. Xue. 1999. Infiltration Through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity, EPA/600/R-00/016 (page 5-2). Water Supply and Water Resources Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Edison, NJ.

[4] Natural Resources Conservation Service. Undated. Soil Quality Measurement, Guide for Educators (page 3). Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, DC.

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A strategy would be to scatter soil investigation pits throughout the entire property, guided by the apparent variability in soil types, geology, water table levels, bedrock, topography, *etc.*, and then replicate them in order to narrow spacing. If replication should show little variability in some locations but more in others, it would then be reasonable to concentrate the latter set of tests in the areas of greater variability. The soils assessment results should be employed in thorough analysis and specification of erosion and sedimentation controls pertaining to the construction phase and in hydrologic modeling for both the construction and finished conditions. This letter discusses these subjects below. O-6.3-7 Cont.

CONSTRUCTION-PHASE STORMWATER MANAGEMENT DEFICIENCIES

The documents demonstrate little analysis of the impending construction environment and present proposed best management practices (BMPs) in only the most generic fashion. San Diego County should require the submittal and approval of a stormwater pollution prevention plan (SWPPP) to address construction-related stormwater issues prior to site development. This step is essential to provide government staff and citizens with sufficient information to make informed judgements about the proposed development. The following paragraphs present my reasoning for this position

Topographic Considerations

The Otay Ranch site is characterized in many parts by extremely steep topographic slopes, including in areas where extensive ground disturbance and building will occur. Slope is a leading factor in soil erosion and sediment loss from a construction site. Thus, it is especially crucial to comprehensively address means of avoiding sediment transport from this site or, at the very least, holding it to a *de minimis* level. Achieving this goal requires careful, detailed analysis and development of a SWPPP incorporating superior BMPs tailored to the site's circumstances.

Construction zones cleared of vegetation and not otherwise stabilized yield much more sediment compared to the original area well covered with plants and to the same area restablized with vegetative cover following construction. Measurements and estimates using a mathematical model (Revised Universal Soil Loss Equation Version 2, RUSLE2) indicate 30 to more than 1000 times as much soil loss can occur after vegetation clearing compared to before clearing. Therefore, one year of construction with no or inadequate erosion controls can release into the environment as much sediment loading as occurred over decades or even centuries before the piece of land was cleared. O-6.3-8

Going further into the matter of slope as an important determinant of erosion, RUSLE2 estimates soil loss potential according to variables representing rainfall characteristics, soils, slope length, vegetation cover, BMPs, and contributing area, in addition to slope steepness. All other factors being equal, the equation predicts the approximate increases in soil loss at different slope gradients given in Table 1. It can be seen that the rate of soil loss escalates greatly with increasing gradient. Slopes in the upper ranges of Table 1, and perhaps higher, do exist in the areas to be disturbed for development at Otay Ranch. Their presence and the related high

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potential soil loss further support my conclusion that, before the project moves forward, there should be full analysis and construction SWPPP development, followed by assessment by the government agencies and the public. O-6.3-8 Cont.

Table 1. Comparison of Estimated Soil Loss as Slope Increases from 3 Percent

Slope (%)	Estimated Soil Loss Compared to 3% Slope[a]
6	1.8 times
10	3.0 times
14	4.7 times
20	7.0 times
25	8.9 times
30	10.7 times

[a] From Table4-3 of Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder. 1997. Predicting Soil erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook No. 703, U.S. Department of Agriculture, Washington, DC. The example is for a slope 50 ft in length.

Soils and Hydrology

Beyond paying little attention to the topographic challenges to limiting sediment export during construction, the applicant has likewise given little emphasis to the site's soils, specifically to their relative erosiveness. RUSLE2 takes soils and their erosivity property into account with a variable termed the K Factor, an index that quantifies the relative susceptibility of the soil to sheet and rill erosion. Values range from 0.02 for the least erodible soils to 0.64 for the most erodible.[5] Thus, the challenge of erosion on a construction site can vary by more than 30 times due to soils alone. Soil properties affecting K Factor include texture, organic matter content, structure, and saturated hydraulic conductivity. These characteristics must be known for a proper analysis of erosion potential and effective strategizing to defeat it.

As pointed out earlier, soils information for the project has been derived only from the NRCS soil survey, and site-specific soils characterization is entirely lacking. Without thorough attention to the exact soils that will be disturbed and their relevant characteristics, it is impossible to make a proper assessment of erosiveness and the BMPs that will be necessary to prevent or mitigate it. The soils investigation outlined above should be performed and fully taken into account in site analysis and SWPPP development. O-6.3-9

Producing a truly site-specific SWPPP will require hydrologic modeling of flows to be generated during construction; passed through on-site conveyances; probably held in basins or tanks for flow control, sedimentation and possibly other treatment; and then discharged. This modeling should be performed with the San Diego Hydrologic Model (SDHM) or U.S. Environmental Protection Agency's Storm Water Management Model (SWMM). Resource protection demands that flows are estimated as well as possible to avoid erosion of conveyance channels, to size

[5] Natural Resources Conservation Service. Undated. Updated T and K Factors, Questions & Answers. U.S. Department of Agriculture, Washington, DC.

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equipment correctly, and to protect the receiving waters from high discharges during construction.

It is clear from the documents that this essential hydrologic modeling has not occurred. The agencies with approval responsibilities should not move further with this project until these construction-phase soils and hydrology assessments occur. They must then be incorporated in a project-specific SWPPP, along with the topographic considerations, for proper judgment of an Environmental Impact Report by County staff and citizens. Without perform hydrologic modeling now, the County cannot conclude that the Project's design and mitigation measures will be sufficient to avoid significant water quality impacts (which are discussed below).

Additional Construction-Phase Considerations

The preceding discussion has emphasized the sediment that may issue from the construction site and compromise receiving water quality. Just as the DEIR is incomplete in covering this area, it is equally vague on construction site pollutants besides sediments. These sources include construction materials; wastes produced; and pollutants associated with vehicles and other mechanized equipment, such as fuels, lubricants, and cleaning materials. These substances can introduce toxic pollutants to storm runoff, such as heavy metals, petroleum products, and organic chemicals derived from fossil fuels. A SWPPP should be produced and evaluated before further project consideration, and it should fully detail the BMPs that will be used to control pollutants from these sources.

O-6.3-9 Cont.

DEFICIENCIES IN POST-CONSTRUCTION STORMWATER MANAGEMENT MEASURES

The general tasks for planning stormwater management for the finished development concern conveyance of water across and away from the site, providing sufficient controls to avoid hydromodification impacts on the receiving waters, and preventing or limiting the transport of pollutants associated with human occupancy and activities to waters downstream. The major tools used by analysts in performing these tasks are hydrologic models, algorithms that predict the rates and volumes of runoff resulting from received precipitation and its routing from the point of generation to ultimate discharge. The categories of variables in these models are precipitation quantities and patterns and the characteristics of the land receiving the rainfall. Within the latter category, key variables are topography, surficial land cover, and soils. I have criticized the DEIR's submersion of topographic considerations in a landscape of steep slopes and reliance on soils data not collected on the ground. These deficiencies have negative implications for post-construction stormwater management, which I explore in this portion of my letter.

O-6.3-10

Deficiencies in Assessment of Stormwater Runoff Conveyance

While the DEIR does not lay out in a clear and distinct manner what the final configurations affecting runoff flows will be, it is apparent that some quite steep slopes will remain within the finished development. According to the Manning's Equation commonly used in hydraulics, flow

O-6.3-11

velocity varies as a function of the square root of the slope of the flow path, all other relevant variables being equal. To take two examples from Table 1, above, compared to the velocity on a 3 percent slope, velocity would be approximately 2.6 and 3.3 times as fast on 20 and 30 percent slopes, respectively. According to the Darcy-Weisbach Equation of fluid mechanics, the shear stress at a boundary wall in an open flow channel is proportional to the square of the velocity.[6] Therefore, the respective shear stress levels exerted by flows on 20 and 30 percent slopes would be approximately $2.6^2 = 6.8$ and $3.3^2 = 10.9$ times the shear stress at 3 percent.

Shear stress is responsible for erosion of the bed and banks of channels and streams. The examples given signify how the challenge of maintaining conveyance channels is compounded in steep terrain. At discharge points of these channels (*e.g.*, Jamul and Proctor Valley Creeks), high velocities can do additional erosion damage. The DEIR does not examine these issues, other than making a statement on page 11 of Appendix 3.1.2-2 (Major Stormwater Management Plan) that, "These changes [to drainage patterns] will be mitigated by the proposed storm drain system consisting of inlets, pipes, cleanouts, energy dissipation, and basins." This statement is conclusory and does not demonstrate that this system will be properly designed to prevent downstream erosion. Those reviewing this large and complex development proposal in a difficult setting deserve much more extensive and thoughtful analysis. O-6.3-11 Cont.

Deficiencies in Proposed Pollutant Source Controls

Fertilizers, lawn and garden pesticides, pet wastes, and washing vehicles at home are all common and significant sources of pollutants in stormwater flowing from urban communities. They should first be addressed by specification of effective source controls, with reliance on stormwater treatment being secondary. The DEIR is nearly silent on control of these sources. It devotes only four sentences in section 3.1.2 (Hydrology and Water Quality) and Appendix 3.1.2-2 (Major Stormwater Management Plan) stating that residents and the homeowners' association will be encouraged to minimize use of fertilizers and pesticides and discouraged from washing cars at home. There is no mention of controlling pet wastes. The documents provide no evaluation of how effective these measures might be or what mechanisms will or could be put in place to raise their success. O-6.3-12

Deficiencies in Modeling for Hydromodification and Water Quality Control

Extensive hydrologic modeling lies at the heart of the DEIR's provisions for both post-construction hydromodification and water quality control. Soils data are important inputs to the computerized, quantitative models. As already pointed out, though, no site-specific soils data have been collected. Earlier in this letter I have given reasons why these data should be gathered and used in analyzing the project's potential environmental impacts, developing strategies to avoid or greatly limit negative impacts, and specifying practices to do so. The DEIR contains more documentation for post-construction hydromodification and water quality control than for construction-phase stormwater management. In the end, though, the prescriptions rest on soils data that may or may not well represent the site. Allowing verification of their utility to actually O-6.3-13

[6] Chaudhry, M.H. 2013. *Applied Hydraulic Transients*, 3rd Ed. Springer Publishing Company, New York, NY.

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reduce impacts to non-significance is another reason why the soils investigations I have described should be performed. The results should be used in model reruns and output interpretation to finalize practice selections for hydromodification and water quality control. O-6.3-13 Cont.

Deficiencies in Proposed Treatment for Stormwater Runoff Water Quality Control

Both hydromodification and water quality control for Otay Ranch rest largely on 14 basins, termed by the DEIR "biofiltration basins". These basins will have detention capacity and outlet structures to regulate the stormwater runoff release rates to accomplish hydromodification control. For water quality treatment, runoff quantities produced by rainfall up to and including the water quality design storm will percolate through 18 inches of soil engineered to enhance pollutant capture. The pollutant removal mechanisms in the soil are additional to particle settling in the detention zone and filtering and biological actions provided by vegetation contact. Seven of the basins will be lined to isolate them from the lower soil; the remainder will be constructed on soils believed to be the most impervious and will not be lined. The percolating water will be collected in perforated underdrain piping and discharged through the surface drain system to the receiving waters downstream. O-6.3-14

To explain this operational plan further, the water quality design is scaled for more-frequent, smaller storms (design storm) but not the less-frequent, large storms that produce more runoff per event. In work that I have done in the past I calculated that the design storm used in the DEIR analysis (the 85th percentile, 24-hour event) represents approximately 62 percent of the average annual rainfall quantity for San Diego.[7] Therefore, about 38 percent of the runoff generated over an extended period encompassing multiple storms at Otay Ranch would bypass to the discharge without passing through treatment. The water percolating through the basin to the bed (a portion of the 62 percent receiving treatment, reduced in quantity by whatever fraction evaporates and transpires to the atmosphere as vapor) would still discharge. A North Carolina study of a treatment system of the type planned for Otay Ranch, lined and fitted with an underdrain, measured the evapotranspiration (ET) fraction as 21-29 percent.[8] In my judgment ET in the San Diego area during the wet season would tend to be on the high side of this range. For my analysis I took the maximum in the study's range and rounded to 30 percent. O-6.3-15

The project proponent's analysis actually estimates a lower percentage of average annual runoff retention than I calculated. The Summary of Stormwater Pollutant Control Calculations (V1.3) in Appendix 3.1.2-2 (Major Stormwater Management Plan) estimates retention to be as low as 4.6 percent in the seven basins having bed liners, with the highest values being 36.3 percent in a large basin and 58.8 percent in a small- to medium-size facility. I weighted the retention percentages according to the respective basin volumes and found that the overall capture according to the proponent's calculations would be 16.2 percent. The DEIR presents the entire site as not supportive of infiltration BMPs, based on some infiltration testing at some basin sites.

[7] Horner, R.R. and J. Gretz. 2011. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices Applied to Meet Various Potential Stormwater Runoff Regulatory Standards. Natural Resources Defense Council, Santa Monica, CA.
[8] Sharkey, L.J. 2006. The Performance of Bioretention Areas in North Carolina: A Study of Water Quality, Water Quantity, and Soil Media. Thesis, North Carolina State University, Raleigh, NC.

The mass of a contaminant in a runoff stream is the multiplication product of the flow volume and pollutant concentration (mass/unit volume). Using these data, the total pollutant mass generated by a storm event (M_T) and the mass remaining to discharge (M_D) can be expressed in equation form, respectively, as:

$$M_T = [(V)(C_{in})]$$

M_D = Total pollutant mass generated – Mass removed by evapotranspiration – Mass removed by treatment processes

$$M_D = M_T - [(1 - f_1)(f_2)(V)(C_{in})] - [(1 - f_1)(1 - f_2)(V)(C_{in} - C_{out})]$$

Where: M_T = Total pollutant mass generated
M_D = Pollutant mass discharged
f_1 = Fraction of flow larger than design storm (0.38)
V = Flow volume
f_2 = Fraction of flow evaporated and transpired as a vapor (0.30)
C_{in} = Pollutant concentration entering treatment
C_{out} = Pollutant concentration exiting treatment

The pollutant loading reduction efficiency (E, %) is then $E = [(M_T - M_D)(100)]/ M_T$.

To estimate the effectiveness of the proposed Otay Ranch treatment system, I drew on the International Stormwater Best Management Practice Database[9] to obtain concentration data for C_{in} and C_{out}, using the median values from the full data set for treatment of the type planned. I used a unit volume, which is not a factor since volume appears in every term in the efficiency equation and thus cancels out. Table 2 gives the results.

It may be seen that the system designed to treat runoff produced by events up to and including the 85th percentile, 24-hour storm would reduce by about half, compared to the development with no treatment, the mass discharge of total suspended solids, zinc, and the bacterial indicators enterococci and *Escherichia coli*. The copper and nitrogen reductions would be less, and phosphorus would actually be expected to increase (*i.e.*, undergo negative reduction) after treatment. If the evapotranspired fraction of the flow is as low as 16.2 percent, instead of the 30 percent I used in my analysis, the pollutant removal efficiencies would drop by several percentage points. O-6.3-15 Cont.

These results point out the main shortcoming of underdrained biofiltration systems built with compost-amended soils: relatively poor or even negative removal of the nutrients responsible for eutrophication, like phosphorus and nitrogen. These nutrients come from vegetation decomposition and the compost itself. As covered in detail later, Otay Ranch's receiving waters, O-6.3-16

[9] International Stormwater BMP Database, 2016 Summary Statistics, http://www.bmpdatabase.org/Docs/03-SW-1COh%20BMP%20Database%202016%20Summary%20Stats.pdf (last accessed November 27, 2017).

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especially the Lower Otay Reservoir, are vulnerable to the pollutants that would not be removed at high levels, and in some cases are listed as impaired by these contaminants.

Table 2. Estimated Pollutant Mass Removal Efficiencies of Proposed Otay Ranch Biofiltration Basins

Pollutant	Unit	C_{in}[a]	C_{out}[a]	Efficiency[b]
Total suspended solids	mg/L	40.6	10.0	51.3%
Enterococci	Most probable number/100 mL	590	220	45.8%
Escherichia coli	Most probable number/100 mL	1200	240	53.3%
Total recoverable copper	μg/L	9.20	5.70	35.1%
Total recoverable zinc	μg/L	49.8	12.0	51.5%
Total phosphorus	mg/L	0.13	0.24	-18.1%
Total nitrogen	mg/L	1.24	1.04	25.6%

[a] C_{in} = Concentration of pollutant entering treatment; C_{out} = Concentration of pollutant exiting treatment (both in the unit in the unit give).
[b] Percentage of pollutant mass removed.

The text in Appendix 3.1.2-2 (step 6.1) states:

> "Biofiltration basins provide "High" pollutant removal efficiency for all pollutants, except those that tend to be dissolved. This means that the proposed water quality basins have high pollutant removal efficiency for the primary pollutants of concern typically associated for this type of development. Biofiltration facilities provide a medium pollutant (*sic*) efficiency for pollutants that tend to be dissolved such as nutrients."

My analysis demonstrates that these claims are untrue. In no way can efficiencies of no better than about 50 percent be characterized as "high," or can only 25 percent nitrogen capture and actual production of phosphorus be called "medium efficiency." The DEIR is thus incorrect that the development poses less than a significant impact to water quality. In preparing the report the DEIR authors did no quantitative analysis of the type I present in this letter to show how much the proposed treatment system actually could mitigate the pollutants associated with the conversion of open land to a community with all the activity that human presence entails.

I have made no attempt to quantitatively evaluate the impacts of pesticide applications in the development. I can say, though, that pesticide chemicals tend to be associated with the solids in fluid transport. Reduction of total suspended solids by about 50 percent would probably reduce pesticides entrained by stormwater flows by a similar amount, but not more. Therefore, the downstream waters, including the drinking water reservoirs, would receive more of these pollutants too.

O-6.3-16 Cont.

<u>Deficiencies in Cumulative Impact Analysis</u>

Section 3.1.2.3 of the Hydrology and Water Quality segment of the DEIR purports to cover the effects accumulating among Otay Ranch and the other past, present, and future related projects. It concludes, for each of four water resources issues considered, that, "…the Proposed Project's

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incremental effects, in combination with other cumulative projects, **would not be cumulatively considerable** [bold emphasis in original]." However, the analysis is very abbreviated, vague, and entirely qualitative. It does no more than repetitively quote the numbers of development units in the various parcels and presents no evidence to substantiate the conclusion. O-6.3-17 Cont.

ENVIRONMENTAL CONSEQUENCES OF CONSTRUCTION AND POST-CONSTRUCTION STORMWATER MANAGEMENT DEFICIENCIES

Water Pollutants of Concern and Their Sources

Above I determined that the DEIR's provisions for both construction-phase and post-construction stormwater management are inadequate to prevent the introduction of pollutants to stormwater runoff during both periods. Hundreds of water pollutants are associated with urban development and its human facilities and activities. These pollutants fall into the categories of: (1) solid particles, which create their own negative impacts and also transport pollutants in the other categories; (2) nutrients, particularly phosphorus and nitrogen, which can over-enrich receiving waters and cause harmful algae and plant growths; (3) oxygen-demanding materials, which deplete dissolved oxygen needed by aerobic life; (4) metals, some of which, like copper and zinc, are toxic to aquatic life; (5) petroleum products, which have toxic and nuisance effects in receiving waters; (6) organic chemicals, including pesticides and numerous other household and commercial chemicals, again many of them toxic to aquatic organisms as well as humans and wildlife; and (7) pathogenic (disease-causing) organisms.

O-6.3-18

Contaminants from a poorly controlled construction site include sediments, the pollutants for which they are a transport medium, and a host of harmful substances associated with construction materials, wastes, and equipment. These pollutants are in all of the above categories, usually excepting the final one.

Eroded sediments from a construction site deposit in a relatively quiescent location, such as a reservoir, change the character of its bed and, over the long term, reduce its depth. More immediate and serious, though, are the nutrients phosphorus and nitrogen, generally present in soil, which are transported with the eroded particles. When they enter natural water bodies and raise the amounts of these substances present in the water, they can stimulate increased growths of algae and aquatic plants, a process known as eutrophication. Increased nutrient loading to a drinking water reservoir can present major problems, upon which the next section of this letter elaborates.

O-6.3-19

Construction materials, wastes, and equipment permitted to escape in stormwater runoff introduce toxic metals, petroleum products, and organic chemicals. Copper and zinc are relatively soluble metals and at least partially dissolve into runoff when handled and stored in contact with rainfall and runoff. Fueling of vehicles, other equipment, or both almost always occurs on large construction sites. Maintenance and cleaning also sometimes take place. Careless operations release petroleum products, which are then picked up and transported in runoff. Paint, solvents, cleaners, and other chemicals used in construction are sources of toxic organics.

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After a development is occupied, human activities such as vehicular transportation, lawn care, and pet keeping introduce pollutants from several of the categories listed above. Table 3 gives the concentrations of common pollutants associated with these activities measured in urban runoff from land use types that would be present at Otay Ranch, in comparison to drainage from open (undeveloped) land. With the exceptions of total suspended solids (TSS), nitrate+nitrite-nitrogen, and total phosphorus, concentrations in flows from the developed land uses range from 50 percent higher to almost four (4) times as high as open land runoff. Total phosphorus is 20 percent higher in runoff from the prevalent land use proposed at Otay Ranch, residential, than from open land.

Table 3. Median Pollutant Concentrations in Stormwater Runoff from Three Land Use Types from the National Stormwater Quality Database[10]

Pollutant	Unit	Open Space	Residential	Commercial
Total suspended solids	mg/L	51	48	43
Total phosphorus	mg/L	0.25	0.30	0.22
Total Kjeldahl nitrogen[a]	mg/L	0.60	1.40	1.60
Nitrate+nitrite-nitrogen	mg/L	0.60	0.60	0.60
Biochemical oxygen demand	mg/L	4.2	9.0	11.9
Chemical oxygen demand	mg/L	21	55	63
Total copper	μg/L	5	12	17
Total lead	μg/L	5	12	18
Total zinc	μg/L	39	73	150
Fecal coliform bacteria	No./100 mL	3100	7750	4500

[a] Nitrogen in the organic plus inorganic ammonia and ammonium forms.

In addition to concentration (mass/unit volume of water), pollutant mass loading (mass/unit time) is instrumental in water quality. Concentration represents exposure to the contaminant at a point in time and thus is the major factor in acute effects on receptor organisms. Mass loading represents a cumulative exposure over time, creating a chronic stress on life forms and aggregate contaminant collection in a repository such as the aquatic sediments. Loading is the multiplication product of concentration times flow volume over the time period and can be expressed on the basis of unit area (kg/ha-year) or total catchment (kg/year). With the construction of impervious surfaces and lawns in place of native landscapes, urbanization increases runoff volume. Table 3 shows that it generally also increases concentrations. Therefore, we would anticipate seeing substantially elevated pollutant mass loadings in developed versus undeveloped runoff.

Table 4 shows that expectation to be borne out. Loadings from the developed compared to undeveloped land uses are generally about 50-400 percent greater, although ranging much higher for TSS and total phosphorus. The ultimate, long-term burden of unmitigated urban stormwater runoff on water quality is thus a function of both hydrologic modification and release of

O-6.3-20

[10] Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. 2007. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2nd Ed. North American Lake Management Society, Madison, Wisconsin, USA.

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chemical, physical, and biological agents by urban inhabitants and their possessions and activities.

Table 4. Pollutant Loadings in Storm Runoff from Three Land Use Types as Reported in the Stormwater Literature[a]

Pollutant	Unit	Undeveloped[b]	Residential[c]	Commercial
Total suspended solids	kg/ha-year	3	250	1000
Total phosphorus	kg/ha-year	0.03	0.3	1.5
Total Kjeldahl nitrogen	kg/ha-year	2.5 as total nitrogen*	2.5	6.7
Nitrate+nitrite-nitrogen	kg/ha-year		1.4	3.1
Biochemical oxygen demand	kg/ha-year	NA[d]	27	62
Chemical oxygen demand	kg/ha-year	NA[d]	50	420
Total copper	kg/ha-year	0.01**	0.03	0.40
Total lead	kg/ha-year	0.005	0.05	2.7
Total zinc	kg/ha-year	0.03**	0.10	2.1
Fecal coliform bacteria***	No./ ha-year	1.0×10^{10}	3.8×10^{10}	2.4×10^{10}

[a] Source: Burton, G.A., Jr. and R.E. Pitt. 2002. *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*. Lewis Publishers, Boca Raton, FL (Table 2.5), except:

* Beaulac, M.N. and K.H. Reckhow. 1982. An Examination of Land Use - Nutrient Export Relationships. *Journal of the American Water Resources Association* 18:1013-1024.

** Wanielista, M.P. and Y.A. Yousef. 1993. *Stormwater Management*. John Wiley and Sons, Inc., New York, New York, USA (Table 5.19).

*** Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. 2007. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2[nd] Ed. North American Lake Management Society, Madison, Wisconsin, USA (Table 3-13).

[b] "Woodland" for total copper and total zinc; "parks" for total suspended solids, total phosphorus, and total lead; "forest" for remaining pollutants (Note: Multiple sources were consulted for the undeveloped category since data for the various pollutants were not reported in consistent land use terms.).

[c] Medium-density residential (approximately 20 percent impervious).

[d] Not available.

O-6.3-20 Cont.

The Negative Effects of Reservoir Eutrophication

The nutrients, toxic substances, oxygen-demanding materials, and bacteria flowing into a drinking water reservoir, such as the Upper and Lower Otay Reservoirs, can present numerous problems negatively affecting its water quality and the treatment and use of its potable water product. Eutrophication caused by nutrient additions elevating algal growth is a particular challenge, and is discussed first.

O-6.3-21

The growth of an aquatic photosynthesizing primary producer (an algal cell, a plant) tends to be controlled by, more than any other agent, the nutrient in least supply relative to the physiological need, known as the limiting nutrient. That nutrient is generally either phosphorus (P) or nitrogen (N), but in fresh waters is more often P. N still can be limiting at times, for example when high algal biomass incorporates much of the P supply, leaving little available in the water. In a reservoir, algae are by far the major primary producers, because there is usually little relatively shallow water in which rooted plants can grow. The remaining discussion concentrates on algae.

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Addition of the limiting nutrient not only increases algal abundance but also tends to change the community from single-celled organisms to filamentous forms, which are less desirable for several reasons. They are generally an inferior food source for wildlife; clog water intakes, conveyances, and boat motors; and foul beaches when they wash up on them. Some filamentous blue-green algae produce toxins that can kill an animal that drinks directly from the water and must be removed before distributing to humans.

When the increased masses of algae die, bacteria decomposing them exert a large demand on the oxygen dissolved in the water and reduce the amount available for aquatic life. Other sources of organic material issuing from a construction site or urban community supplement this oxygen demand. It is not unusual for a eutrophic reservoir, lake, or estuary to have little or sometimes no oxygen in the colder waters at the bottom, and reduced oxygen even near the surface. An anaerobic condition at the water-sediment interface along the reservoir bed enables chemical reactions that release a variety of deleterious pollutants into the water column. One of these substances is phosphorus, which stimulates further algal growth. Thus, eutrophication sets up a feedback loop compounding the problem.

It has been well recognized for more than 35 years that eutrophication creates myriad and complex problems in a drinking water reservoir and the water supply system it feeds. Walker (1983) published a review drawing upon many papers and reports in the scientific and technical literature.[11] He presented data from 38 U.S. reservoirs and lakes showing that median total phosphorus concentration explains 85 percent of the variance in median total organic carbon (TOC) concentration, a sum of the particulate organic carbon (POC) and dissolved organic carbon (DOC). His paper starkly illuminated the resulting problems, which lie in three general areas, namely impacts on: (1) water in the reservoir, (2) water utility operations, and (3) water users.

O-6.3-21 Cont.

Nutrient enrichment and the resulting algal growth affect reservoir water quality, having further implications for operations and consumers, by:

- Increasing the POC content (the algal cells themselves);
- Increasing the DOC content (excretions from algal cells);
- Shifting the algal composition toward less desirable forms (*e.g.*, blue-greens);
- Increasing daytime pH, through heightened extraction of carbon dioxide during photosynthesis by the abundant algae;[12] and

[11] Walker, W.W., Jr. 1983. Significance of Eutrophication in Water Supply reservoirs. *Journal of the American Water Works Association* 75(1):38-42.

[12] Removal of carbon dioxide from the water raises pH through reduction of bicarbonate, a buffering agent, which chemically dissociates to replenish the lost carbon dioxide. The rise of water pH also drives ammonia toward the unionized form (NH_3), which is more toxic to aquatic life than ionized ammonia (NH_4^+).

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- Through oxygen depletion at the sediments, releasing not only phosphorus but also ammonia, iron, manganese, other metals, hydrogen sulfide, methane, and other organic compounds.

These reservoir water quality modifications have direct and indirect effects on water supply operations and treatment costs, as follows:

- Hindering of the particle aggregation process in the treatment plant by higher particulate load (mainly, algal cells), DOC, and increased need for costly chemical treatment;[13]
- Hindering of the filtration process in the treatment plant by higher particulate load, faster clogging, reduced filter run times, and the energy and water-loss costs of increased backwashing;
- Hindering of the disinfection process by creating increased chlorine demand and lowering effectiveness owing to organic matter, ammonia, and turbidity;
- Producing a contaminant in the treatment process itself, chlorinated hydrocarbons, which result from the reaction of chlorine with DOC (having negative human health effects covered below); O-6.3-21 Cont.
- Hindering of the water distribution process by regrowth of bacteria on the increased organic carbon substrate and taste and odor problems stemming from organic decomposition, iron, and manganese; and
- All of these problems leading to the burden and costs of increased monitoring, special treatments (*e.g.*, for chlorinated hydrocarbons, iron, manganese, taste, and odor), and extra reservoir management (*e.g.*, algicide application, aeration).

Finally, without effective amelioration of these problems, water users can suffer from:

- Exposure to potentially carcinogenic, mutagenic, or otherwise toxic chlorinated hydrocarbons;
- Exposure to potentially pathogenic microorganisms;
- Unpleasant taste and odor;

[13] Aggregation is the process of combining smaller, less easily settled particles to form larger, denser, more easily settled masses through coagulation (reducing the forces responsible for keeping particles apart) and flocculation (bringing the particles together to form aggregates). For information on how eutrophication negatively affects coagulation, see: Cheng, W.P. and F.H. Chi. 2003. Influence of Eutrophication on the Coagulation Efficiency in Reservoir Water. *Chemosphere* 53:773–778.

- Plumbing and clothing damage by iron and manganese deposition and corrosion by organics;
- The need for quality-sensitive industrial users to install special treatment; and
- Higher utility bills to cover the increased costs of reservoir and treatment plant operations.

Chlorinated hydrocarbon formation is an especially worrisome problem. The formation of these chemicals has been shown to be strongly associated with the amount of TOC (made up of algae, its excretions, and other organic substances) in chlorinated water supplies.[14, 15] Individual chemicals in this group are demonstrated or suspected carcinogenic and mutagenic agents. Trihalomethanes (THMs) represent the most recognized and well-studied subset of this chemical category, although they make up only 15-20 percent of all chlorinated hydrocarbon compounds that have been identified in finished potable water samples. Chloroform, a prominent THM, was listed as a suspected human carcinogen by the National Cancer Institute more than 40 years ago. Other chlorinated hydrocarbons besides THMs may also be carcinogenic, mutagenic, or both.

In addition to rising with increased TOC and chlorine dose, THM yield also increases with elevated pH. As stated earlier, the removal of carbon dioxide from water by algal photosynthesis raises pH. Hence, eutrophication of a reservoir raises chlorinated hydrocarbon content by this mechanism as well as by generating more TOC.

There are strong signs that Lower Otay Reservoir is already at least somewhat advanced in eutrophication. Its water quality has been listed under Section 303(d) of the Clean Water Act (CWA) as impaired for ammonia, iron, manganese, and pH. As seen above, elevation of all of these measures is a consequence of eutrophication. Further nutrient additions in stormwater runoff from poorly controlled construction at the project site and the subsequent occupied development would aggravate the Reservoir's already impaired water quality.

O-6.3-21 Cont.

The DEIR gives no attention in any way approaching the discussion here regarding the many-pronged problem of reservoir eutrophication. It does not address how it will be guaranteed that construction will be controlled well enough to avoid sediment transport adding nutrients to the reservoirs during that phase. It further proposes a final land use that could release as much as 10 times the total phosphorus discharge as the current landscape discharges (see Table 4), into a treatment system that the evidence indicates would actually release more phosphorus than it receives (see Table 3). For these reasons, the DEIR fails to show that the development poses less than a significant impact to water quality.

O-6.3-22

[14] Walker, *Ibid.*
[15] Palmstrom, N.S., R.E. Carlson, and G.D. Cooke. 1988. Potential Links Between Eutrophication and the Formation of Carcinogens in Drinking Water. *Lake and Reservoir Management* 4(2):1-15.

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Other Negative Effects on the Reservoirs

Beyond eutrophication, pollutants associated with eroded sediments; construction equipment, materials, and wastes; and runoff from an urban community can negatively affect the resource in many other ways. From the potable water supply standpoint, toxic metals (*e.g.*, lead, cadmium), pesticides, and other organic chemicals either further raise the treatment burden or pass through to risk the health of water consumers. Higher bacterial and viral loads, often from pet wastes and other indirect human-related sources, require more chlorine dosing, feeding back to increases in cost and chlorinated hydrocarbon production.

Lower Otay Reservoir has several stocked fish populations and a recreational fishery. Pelagic fish in a reservoir or lake are vulnerable to sediment transport in several ways. First, of course, particulates are a transport medium for other pollutants, specifically the toxins of construction and urban development origin. When settling, they alter the lake bed physically and chemically, to the particular detriment of fish usually or sometimes occupying that zone. Suspended particles reduce light penetration and visibility, making it harder for fish to feed and avoid predators. They abrade soft tissues, especially gills, and also introduce toxic agents at the gill surface, where they are easily assimilated into the body.

Fish are sensitive to the same metallic and organic toxicants risking the health of human water consumers. In addition, they are very vulnerable to other common stormwater contaminants well-tolerated by humans and other mammals, especially copper and zinc. There is a large literature on the specific lethal and negative sublethal effects of metals on fish and other aquatic life. Concentrations of copper and zinc often measured in urban runoff cause sublethal but still harmful effects on the life cycle processes of feeding and growth, ability to avoid predators, resistance to disease, reproduction, and rearing (see, for example, Baldwin *et al.*,[16] Chapman,[17] and Price[18]). O-6.3-23

The negative effects of metal toxins are not necessarily limited to short-term, acute lethal or medium-term sublethal impacts. Over time an organism can accumulate metals in tissue, a process known as bioaccumulation. When predators consume organisms with bioaccumulated metals, they concentrate them in their tissues. The top predator in an aquatic ecosystem tends to have the highest concentrations, through biomagnification up the food chain.

Aquatic sediments become repositories for particulate metals through gravity settling and for dissolved metals through various adsorption and ion exchange processes. In addition to their toxicity to bottom-dwelling organisms, these captured metals can become remobilized into the

[16] Baldwin, D.H., J.F. Sandahl, J.S. Labenia, and N.L. Scholz. 2003. Sublethal effects of copper on coho salmon: Impacts on nonoverlapping receptor pathways in the peripheral olfactory nervous system. *Environmental Toxicology and Chemistry* 22(10):2266-2274.

[17] Chapman, G.A. 1978. Toxicities of cadmium, copper, and zinc to four juvenile stages of Chinook salmon and steelhead. *Transactions of the American Fisheries Society* 107: 841-847.

[18] Price, M.H.H. 2013. Sub-lethal Metal Toxicity Effects on Salmonids: a review. Report prepared for SkeenaWild Conservation Trust. Smithers, BC, Canada. 64 pages.

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water column by disturbance and dissolution, and thus harm pelagic aquatic life long after their initial release. O-6.3-23 Cont.

The DEIR examines none of these other negative reservoir effects. This omission is another reason for its failure to show that the development poses less than a significant impact to water quality. O-6.3-24

Potential Negative Effects on Other Aquatic Environments

Jamul Creek is listed under CWA Section 303(d) as impaired for toxicity. It drains a large portion of the proposed development area and is tributary to Lower Otay Reservoir. As I showed above, there are many potential sources of toxicity associated with a poorly controlled construction site and a development that does not remove a large share of such toxicants from its runoff. I further demonstrated that the DEIR is highly deficient in giving assurance that the construction will be well-controlled. I went on to show that the proposed permanent stormwater treatment will discharge substantial amounts of the pollutants inevitably generated in an urban development. The toxics thereby released will further impair Jamal Creek. O-6.3-25

Lower Otay Reservoir does not often release water for transport downstream via the Otay River to San Diego Bay and the Pacific Ocean. When it does, though, it would be during and after an especially large rainfall. In those circumstances the wash-off of pollutants from the development would be elevated. Flows would surely be well above the biofiltration treatment system design conditions and would bypass treatment. Greater pollutant generation coupled with lack of treatment would result in high pollutant loadings to the downstream waters. Appendix 3.1.2-2 (Major Stormwater Management Plan, step 3.6) lists bacteria, dissolved copper, lead, and zinc as Highest Priority Pollutants for San Diego Bay. According to DEIR section 3.1.2 (Hydrology and Water Quality), there is concern with bacteria at the Coronado beaches near the bay's mouth. There are also some 303(d) listings for bacterial impairment in the ocean waters to the north and south. As I have been discussing, these pollutants have sources in construction sites and urban areas like the proposed project, which can and, with inadequate control at Otay Ranch, will contribute to exacerbating the current problems. O-6.3-26

These considerations are absent from the DEIR. This absence constitutes yet another reason why it fails to justify its conclusion that the development poses less than a significant impact to water quality.

SUMMARY AND CONCLUSIONS

The DEIR has not adequately justified its assertions of non-significant impacts to the downstream waters that will receive stormwater runoff from Otay Ranch. My reaching this conclusion begins with the inadequacy of analysis of the project's highly challenging topographic setting and the failure to perform any site-specific soils characterization at all. These two considerations are fundamental to proper impact assessment in both the construction phase and the finished condition of the development. O-6.3-27 Attention to managing construction site stormwater runoff is particularly lacking, and the DEIR gives me little confidence that this O-6.3-28

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period will be appropriately controlled to avoid the extensive downstream impacts that could occur. Proposals for hydromodification and water quality controls to be built into the development rely on hydrologic modeling. That modeling in turn depends on, among other input variables, soils data, which have not been collected. Finally, the potential effectiveness of the proposed water quality control system was not examined. My own analysis demonstrates that the proposed system will allow transport downstream of large fractions of the pollutant loadings that are typical of urban development, to waters sensitive and in some cases already impaired by some of the pollutants at issue. Of particular concern is phosphorus export from the project to the water supply reservoirs, increasing eutrophication and its resulting negative implications for reservoir water quality, the City of San Diego's water utility operations, and the risk to San Diego's water consumers of unsafe and disagreeable conditions.

O-6.3-28 Cont.

O-6.3-29

O-6.3-30

I would be pleased to answer any questions you may have and invite you to contact me if you wish.

O-6.3-31

Sincerely,

Richard R. Horner

Richard R. Horner

Attachments: Attachment A; Background and Experience; Richard R. Horner, Ph.D.
Attachment B; *Curriculum Vitae*
Attachment C; County of San Diego BMP Design Manual (excerpted)

ATTACHMENT A

Background and Experience

RICHARD R. HORNER, PH.D.

I have 51 years of professional experience, 45 teaching and performing research at the college and university level. For the last 40 years I have specialized in research, teaching, and consulting in the area of storm water runoff and surface water management.

I received a Ph.D. in Civil and Environmental Engineering from the University of Washington in 1978, following two Mechanical Engineering degrees from the University of Pennsylvania in 1965 and 1966. Although my degrees are all in engineering, I have had substantial course work and practical experience in aquatic biology and chemistry.

For 12 years beginning in 1981, I was a full-time research professor in the University of Washington's Department of Civil and Environmental Engineering. From 1993 until 2011, I served half time in that position and had adjunct appointments in two additional departments (Landscape Architecture and the College of the Environment's Center for Urban Horticulture). I spent the remainder of my time in private consulting through a sole proprietorship. My appointment became emeritus in late 2011, but I continue university research and teaching at a reduced level while maintaining my consulting practice.

My research, teaching, and consulting embrace all aspects of stormwater management, including determination of pollutant sources; their transport and fate in the environment; physical, chemical, and ecological impacts; and solutions to these problems through better structural and non-structural management practices.

I have conducted numerous research investigations and consulting projects on these subjects. Serving as a principal or co-principal investigator on more than 40 research studies, my work has produced three books, approximately 30 papers in the peer-reviewed literature, and over 20 reviewed papers in conference proceedings. I have also authored or co-authored more than 80 scientific or technical reports.

In addition to graduate and undergraduate teaching, I have taught many continuing education short courses to professionals in practice. My consulting clients include federal, state, and local government agencies; citizens' environmental groups; and private firms that work for these entities, primarily on the West Coast of the United States and Canada but in some instances elsewhere in the nation.

Over a 17-year period beginning in 1986 I spent a major share of my time as the principal investigator on two extended research projects concerning the ecological responses of freshwater resources to urban conditions and the urbanization process. I led an interdisciplinary team for 11 years in studying the effects of human activities on freshwater wetlands of the Puget Sound lowlands. This work led to a comprehensive set of management guidelines to reduce negative effects and a published book detailing the study and its results. The second effort involved an analogous investigation over 10 years of human effects on Puget Sound's salmon spawning and rearing streams. These two research programs have had broad sponsorship, including the U.S. Environmental Protection Agency, the Washington Department of Ecology, and a number of local governments.

I have helped to develop stormwater management programs in Washington State, California, and British Columbia and studied such programs around the nation. I was one of four principal participants in a U.S. Environmental Protection Agency-sponsored assessment of 32 state, regional, and local programs spread among 14 states in arid, semi-arid, and humid areas of the West and Southwest, as well as the Midwest, Northeast, and Southeast. This evaluation led to the 1997 publication of "Institutional Aspects of Urban Runoff Management: A Guide for Program Development and Implementation" (subtitled "A Comprehensive Review of the Institutional Framework of Successful Urban Runoff Management Programs").

My background includes 23 years of work in California, where I have been a federal court-appointed overseer of stormwater program development and implementation at the city and county level and for two California Department of Transportation districts. I was directly involved in the process of developing the 13 volumes of Los Angeles County's Stormwater Program Implementation Manual, working under the terms of a settlement agreement in federal court as the plaintiffs' technical representative. My role was to provide quality-control review of multiple drafts of each volume and contribute to bringing the program and all of its elements to an adequate level. I have also evaluated the stormwater programs in San Diego, Orange, Riverside, San Bernardino, Ventura, Santa Barbara, San Luis Obispo, and Monterey Counties, as well as a regional program for the San Francisco Bay Area. At the recommendation of San Diego Baykeeper, I have been a consultant on stormwater issues to the City of San Diego, the San Diego Unified Port District, and the San Diego County Regional Airport Authority.

I was a member of the National Academy of Sciences-National Research Council ("NAS-NRC") committee on Reducing Stormwater Discharge Contributions to Water Pollution. NAS-NRC committees bring together experts to address broad national issues and give unbiased advice to the federal government. The present panel was the first ever to be appointed on the subject of stormwater. Its broad goals were to understand better the links between stormwater discharges and impacts on water resources, to assess the state of the science of stormwater management, and to apply the findings to make policy recommendations to the U.S. Environmental Protection Agency relative to municipal, industrial, and construction stormwater permitting. My principal contribution to the committee's final report, issued in October 2008, was the chapter presenting the committee's recommendations for broadly revamping the nation's stormwater program.

ATTACHMENT B

CURRICULUM VITAE

HORNER, Richard Ray

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University of Washington:
Emeritus Research Associate Professor,
Departments of Landscape Architecture and Civil and Environmental Engineering and
Sole Proprietor Consultant

EDUCATION

1976 - 1978 University of Washington, Seattle, Washington; Ph.D. (Civil Engineering)

1965 - 1966 University of Pennsylvania, Philadelphia, Pennsylvania; M.S. (Mechanical Engineering)

1961 - 1965 University of Pennsylvania, Philadelphia, Pennsylvania; B.S. *Cum Laude* (Mechanical Engineering)

HONORS AND AWARDS

Augustus Trask Ashton Scholarship, University of Pennsylvania, 1961 - 65
Annual Academic Honors, University of Pennsylvania, 1961 - 65
Tau Beta Pi National Engineering Honor Society
National Science Foundation Traineeship, University of Pennsylvania, 1965 - 66

EMPLOYMENT

1986 - Present Richard R. Horner, Sole Proprietor (offering services in environmental engineering and science)

2011 - Present University of Washington, Seattle, Washington
Emeritus Research Associate Professor

1981 - 2011 University of Washington, Seattle, Washington
Research Associate Professor

1986 - 1990 King County, Seattle, Washington
Coordinator of Puget Sound Wetland and Stormwater Management Research Program (part-time; continued under contract to University of Washington)

1969 - 1981 Northampton Community College, Bethlehem, Pennsylvania
Engineering Department (Coordinator, 1971 - 73 and 1978 - 79)
Environmental Studies Department (Co-coordinator, 1973 - 76 and 1978 - 1981)
Professor, 1978 - 1981; Associate Professor, 1973 - 78;
Assistant Professor, 1969 - 73,
Leave of Absence, 1977 - 78; Sabbatical Leave, 1976 - 77

1977 - 1978	University of Washington, Seattle, Washington Department of Civil Engineering Research Engineer, Highway Runoff Water Quality Project
1976 - 1977	University of Washington, Seattle, Washington Department of Civil Engineering and Institute for Environmental Studies Research Assistant and Teaching Assistant
1966 - 1969	Exxon Research and Engineering Company, Florham Park, New Jersey; Project Engineer
1965 - 1966	University of Pennsylvania, Philadelphia Pennsylvania Department of Mechanical Engineering; Research Assistant

NATIONAL COMMITTEES

National Academy of Sciences Panel on Reducing Stormwater Discharge Contributions to Water Pollution, 2007-2008.

Technical Advisory Panel for Water Environment Federation projects on Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction, 2005-2007.

Co-chair, Engineering Foundation Conference on Effects of Watershed Development and Management on Aquatic Ecosystems, 1996.

National Academy of Sciences Panel on Costs of Damage by Highway Ice Control, 1990-91.

U.S. Environmental Protection Agency National Wetland Research Planning Panel, 1988, 1991.

RESEARCH PROJECTS

* Principal Investigator.
** Co-Principal Investigator. (Where undesignated, I was a member of the faculty investigation team without principal investigator status).

Effects of Waterfront Stormwater Solutions Prototypes on Water Quality Runoff in Puget Sound near Pomeroy Park - Manchester Beach; Washington Sea Grant; $148,838; 2015-2016.

Development of a Stormwater Retrofit Plan for Water Resources Inventory Area (WRIA) 9 and Estimation of Costs for Retrofitting all Developed Lands of Puget Sound; U.S. Environmental Protection Agency and King County (WA); $243,619; 2010-2013.

Ultra-Urban Stormwater Management; Seattle Public Utilities; $1,130,000; 1999-2008.*

Roadside Vegetation Management Study; Washington State Department of Transportation; $50,000; 2004-2005.

The Ecological Response of Small Streams to Stormwater and Stormwater Controls; U. S. Environmental Protection Agency, cooperating with Watershed Management Institute (Crawfordsville, FL); $579,117; 1995-2003.*

Vegetated Stormwater Facility Maintenance; Washington State Department of Transportation; $86,000; 1998-2000.*

Roadside Drainage System Management for Water Quality Improvement; King and Snohomish (WA) Counties; $70,000; 1997-2000.*

Standardization of Wet Weather Protocols for Stream Impact and Treatment Technology Performance Assessments; Water Environment Research Foundation, cooperating with Water Research Center (Huntington Valley, Pennsylvania) and University of Illinois; $125,000; 1996-97.

Road Shoulder Treatments for Water Quality Protection; Washington State Department of Transportation and King County Roads Division; $90,000; 1995-96.**

Control of Nuisance Filamentous Algae in Streams by Invertebrate Grazing; National Science Foundation; $193,691; 1994-96.

Criteria for Protection of Urban Stream Ecosystems; Washington Department of Ecology; $230,000; 1994-96.

Region-Specific Time-Scale Toxicity in Aquatic Ecosystems; Water Environment Research Foundation, cooperating with Water Research Center (Huntington Valley, Pennsylvania) and University of Illinois; $670,000; 1994-96.

Establishing Reference Conditions for Freshwater Wetlands Restoration; U. S. Environmental Protection Agency; $75,000; 1993-1997.

Stormwater Management Technical Assistance to Local Governments; Washington Department of Ecology; $115,000; 1992-93.*

Center for Urban Water Resources Management; Washington Department of Ecology; $336,490; plus $157,400 matching support from seven local governments; 1990-93.*

University of Washington Cooperative Unit for Wetlands and Water Quality Research; King County, Washington; amount varied by year; 1987-1995.*

Assessment of Portage Bay Combined Sewer Overflows; City of Seattle; $132,676; 1990-91.*

Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase 3; National Science Foundation; $108,332; 1988-90.**

Design of Monitoring Programs for Determining Shellfish Bed Bacterial Contamination Problems; Washington Department of Ecology; $12,000; 1988-89.*

Puget Sound Protocols Development; Tetra Tech, Inc. and Puget Sound Estuary Program; $10,144; 1988.*

Improving the Cost Effectiveness of Highway Construction Site Erosion/ Pollution Control, Phase 2; Washington State Department of Transportation; $97,000; 1987-89.*

Wetland Mitigation Project Analysis; Washington State Department of Transportation; $74,985; 1987-89.*

Lake Chelan Water Quality Assessment; Harper-Owes, consultant to Washington State Department of Ecology; $42,977; 1986-88.

Quality of Management of Silver Lake; City of Everett; $67,463; 1986-88.

Effectiveness of WSDOT Wetlands Creation Projects; Washington State Department of Transportation; $42,308; 1986-87.*

Improving the Cost Effectiveness of Highway Construction Site Erosion/Pollution Control; Washington State Department of Transportation; $41,608; 1986-87.*

Management Significance of Bioavailable Phosphorus in Urban Runoff; State of Washington Water Research Center and Municipality of Metropolitan Seattle; $32,738; 1986-87.**

Environmental Monitoring and Evaluation of Calcium Magnesium Acetate (CMA); Transportation Research Board of National Academy of Sciences; $199,943; 1985-87.*

Conceptual Design of Monitoring Programs for Determination of Water Quality and Ecological Change Resulting from Nonpoint Source Discharges; Washington State Department of Ecology; $49,994; 1985-86.**

Development of an Integrated Land Treatment Approach for Improving the Quality of Metalliferous Mining Wastewaters; Washington Mining and Mineral Resources Research Institute; $4,000; 1985-86.*

Preliminary Investigation of Sewage Sludge Utilization on Roadsides; Washington State Department of Transportation; $6,664; 1984-85.*

Source Control of Transit Base Runoff Pollutants; Municipality of Metropolitan Seattle; $26,867; 1984-85.**

Lake Sammamish Future Water Quality; Municipality of Metropolitan Seattle; $28,500; 1984-85.

Implementation of Highway Runoff Water Quality Research Results; Washington State Department of Transportation; $13,998; 1984-85.*

Performance Evaluation of a Detention Basin and Coalescing Plate Oil Separator for Treating Urban stormwater Runoff; Washington State Water Research Center; 1984-85; $11,724.**

Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase 2; National Science Foundation; $99,088; 1983-85.**

Development of a Biological Overland Flow System for Treating Mining Wastewaters; Washington Mining and Mineral Resources Research Institute; $6,030; 1983-84.*

Nutrient Contributions of Agricultural Sites to the Moses Lake System; Moses Lake Conservation District; $15,039; 1982-84.*

Planning Implementation of Runoff Water Quality Research Findings; Washington State Department of Transportation; $12,735; 1982-83.**

Transport of Agricultural Nutrients to Moses Lake; Brown and Caldwell Engineers; $22,725; 1982-83.**

Investigation of Toxicant Concentration and Loading Effects on Aquatic Macroinvertebrates; University of Washington Graduate School Research Fund; $3,788; 1982.*

Sampling Design for Aquatic Ecological Monitoring; Electric Power Research Institute; $542,008; 1981-86.

Velocity-Related Critical Phosphorus Concentrations in Flowing Water; National Science Foundation; $70,310; 1980-82.

Highway Runoff Water Quality; Washington State Department of Transportation; $461,176; 1977-82.

BOOKS

Shaver, E., R. Horner, J. Skupien, C. May, and G. Ridley. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*, 2nd Edition. U.S. Environmental Protection Agency, Washington, D.C., 2007.

Azous, A. L. and R. R. Horner. *Wetlands and Urbanization: Implications for the Future*. Lewis Publishers, Boca Raton, FL, 2000.

Horner, R. R., J. J. Skupien, E. H. Livingston, and H. E. Shaver. *Fundamentals of Urban Runoff Management: Technical and Institutional Issues*. Terrene Institute, Washington, D. C., 1994.

REFEREED JOURNAL PUBLICATIONS AND BOOK CHAPTERS

Chapman, C. and R.R. Horner. Performance Assessment of a Street-Drainage Bioretention System. *Water Environment Research* 82(2): 109-119, 2010.

Horner, R. R. et al. Structural and Non-Structural Best Management Practices (BMPs) for Protecting Streams. In *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation*, B. K. Urbonas (ed.), American Society of Civil Engineers, New York, pp. 60-77, 2002.

Comings, K. J., D. B. Booth, and R. R. Horner. Storm Water Pollutant Removal by Two Wet Ponds in Bellevue, Washington. *Journal of Environmental Engineering* 126(4):321-330, 2000.

Anderson, E. L., E. B. Welch, J. M. Jacoby, G. M. Schimek, and R. R. Horner. Periphyton Removal Related to Phosphorus and Grazer Biomass Level. *Freshwater Biology* 41:633-651, 1999.

Horner, R. R., D. B. Booth, A. Azous, and C. W. May. Watershed Determinants of Ecosystem Functioning. In *Effects of Watershed Development and Management on Aquatic Ecosystems*, L. A. Roesner (ed.), American Society of Civil Engineers, New York, pp. 251-274, 1997.

Horner, R.R. Toward Ecologically Based Urban Runoff Management. In *Urban Runoff and Receiving Systems*, E.E. Herricks (ed.), Lewis Publishers, Boca Raton, Florida, pp. 365-378, 1995.

Walton, S. P., E. B. Welch, and R. R. Horner. Stream Periphyton Response to Grazing and Changes in Phosphorus Concentration. *Hydrobiologia* 302:31-46, 1994.

Reinelt, L. E. and R. R. Horner. Pollutant Removal from Stormwater Runoff by Palustrine Wetlands Based on a Comprehensive Budget. *Ecological Engineering* 4:77-97, 1995.

Horner, R.R. and M.V. Brenner. Environmental Evaluation of Calcium Magnesium Acetate for Highway Deicing Applications. *Resources, Conservation and Recycling* 7:213-237, 1992.

Brenner, M.V. and R.R. Horner. Effects of Calcium Magnesium Acetate on Dissolved Oxygen in Water. *Resources, Conservation and Recycling* 7:239-265, 1992.

Reinelt, L.E., R.R. Horner, and R. Castensson. Nonpoint Source Water Quality Management: Improving Decision-Making Information through Water Quality Monitoring. *Journal of Environmental Management* 34:15-30, 1992.

Horner, R.R., M.V. Brenner, R.B. Walker, and R.H. Wagner. Environmental Evaluation of Calcium Magnesium Acetate. In *Calcium Magnesium Acetate (CMA): An Emerging Bulk Chemical for Multi-purpose Environmental Applications*, D.L. Wise, Y.A. Lavendis, and M. Metghalchi (eds.), Elsevier Science Publishers B.V., The Netherlands, pp. 57-102, 1991.

Horner, R.R., E.B. Welch, M.R. Seeley, and J.M. Jacoby. Responses of Periphyton to Changes in Current Velocity, Suspended Sediments and Phosphorus Concentration. *Freshwater Biology* 24:215-232, 1990.

Horner, R.R. Long-Term Effects of Urban Stormwater on Wetlands. In *Design of Urban Runoff Quality Controls*, L.A. Roesner, B. Urbonas, and M.B. Sonnen (eds.), American Society of Civil Engineers, New York, pp. 451-466, 1989.

Welch, E.B., R.R. Horner, and C.R. Patmont. Phosphorus Levels That Cause Nuisance Periphyton: A Management Approach. *Water Research* 23(4):401-405, 1989.

Butkus, S.R., E.B. Welch, R.R. Horner, and D.E. Spyridakis. Lake Response Modeling Using Biologically Available Phosphorus. *Journal of the Water Pollution Control Federation* 60(9):1663-1669, 1988.

Reinelt, L.E., R.R. Horner, and B.W. Mar. Nonpoint Source Pollution Monitoring Program Design. *Journal of Water Resources Planning and Management* 114(3):335-352, 1988.

Welch, E.B., J.M. Jacoby, R.R. Horner, and M.R. Seeley. Nuisance Biomass Levels of Periphytic Algae in Streams. *Hydrobiologia*, 157:161-168, 1988.

Reinelt, L.E., R. Castensson, and R.R. Horner. Modification of an Existing Monitoring Program to Address Nonpoint Source Pollution, A Case Study of the Svarta River Basin, Sweden. *Vatten* 43:199-208, 1987.

Mar, B.W., R.R. Horner, J.S. Richey, D.P. Lettenmaier, and R.N. Palmer. Data Acquisition, Cost-Effective Methods for Obtaining Data on Water Quality. *Environmental Science and Technology* 20(6):545-551, 1986.

Horner, R.R., J.S. Richey, and G.L. Thomas. A Conceptual Framework to Guide Aquatic Monitoring Program Design for Thermal Electric Power Plants. *Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Ecosystems*, Special Technical Publication 894 of the American Society for Testing and Materials, Philadelphia, Pennsylvania, pp. 86-100, 1986.

Welch, E.B., D.E. Spyridakis, J.I. Shuster, and R.R. Horner. Declining Lake Sediment Phosphorus Release and Oxygen Deficit Following Wastewater Diversion. *Journal of the Water Pollution Control Federation* 58(1):92-96, 1986.

Richey, J.S., B.W. Mar, and R.R. Horner. The Delphi Technique in Environmental Assessment, Part 1: Implementation and Effectiveness. *Journal of Environmental Management* 21:135-146, 1985.

Richey, J.S., R.R. Horner, and B.W. Mar. The Delphi Technique in Environmental Assessment, Part 2: Consensus on Critical Issues in Environmental Monitoring Program Design. *Journal of Environmental Management* 21:147-159, 1985.

Horner, R.R. and B.W. Mar. Assessing Impacts of Operating Highways on Aquatic Ecosystems. *Transportation Research Record* 1017:47-55, 1985.

Horner, R.R., E.B. Welch, and R.B. Veenstra. Development of Nuisance Periphytic Algae in Laboratory Streams in Relation to Enrichment and Velocity. In *Periphyton of Freshwater Ecosystems*, R.G. Wetzel (ed.), Dr. W. Junk BV, the Hague, The Netherlands, pp. 121-134, 1983.

Horner, R.R. and B.W. Mar. A Guide for Assessing Water Quality Impacts of Highway Operations and Maintenance. *Transportation Research Record* 948:31-40, 1983.

Chui, T.W., B.W. Mar, and R.R. Horner. A Pollutant Loading Model for Highway Runoff. *Journal of Environmental Engineering Division*, ASCE 108:1193-1120, 1982.

Horner, R.R. and E.B. Welch. Stream Periphyton Development in Relation to Current Velocity and Nutrients. *Canadian Journal of Fisheries and Aquatic Sciences* 38:449-457, 1981.

<u>REVIEWED PROCEEDINGS PUBLICATIONS</u>

Horner, R. R. Stormwater Runoff Flow Control Benefits of Urban Drainage System Reconstruction According to Natural Principles. Presentation at Puget Sound—Strait of Georgia Research Conference, Vancouver, B. C., 2003.

May, C.W. and R.R. Horner. 2002. The Limitations of Mitigation-Based Stormwater Management in the Pacific Northwest and the Potential of a Conservation Strategy Based on Low-Impact Development Principles. Proc. 2002 ASCE Stormwater Conference, Portland, OR.

Horner, R. R. and C. R. Horner. Performance of a Perimeter ("Delaware") Sand Filter in Treating Stormwater Runoff from a Barge Loading Terminal. Proc. Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999, pp. 183-192, 1999.

Horner, R. R. and C. W. May. Regional Study Supports Natural Land Cover Protection as Leading Best Management Practice for Maintaining Stream Ecological Integrity. Proc. Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999, pp. 233-248, 1999.

Horner, R. R. Constructed Wetlands for Urban Runoff Water Quality Control. Proc. National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993, pp. 327-340, 1995.

Horner, R. R. Training for Construction Site Erosion Control and Stormwater Facility Inspection. Proc. National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993, pp. 426-450, 1995.

Horner, R. R. Overview of the Puget Sound Wetlands and Stormwater Management Research Program. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 141-145, 1995.

Horner, R. R. and L. E. Reinelt. Guidelines for Managing Urban Wetlands. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 171-178, 1995.

Taylor, B. K. Ludwa, and R. R. Horner. Urbanization Effects on Wetland Hydrology and Water Quality. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995, pp. 146-154, 1995.

Reinelt, L.E. and R.R. Horner. Urban Stormwater Impacts on the Hydrology and Water Quality of Palustrine Wetlands in the Puget Sound Region. Proc. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1991; pp. 33-42.

Horner, R.R. Environmental Effects of Calcium Magnesium Acetate, Emphasizing Aquatic Ecosystem Effects. Proc. Conf. on Environmental Impacts of Highway Deicing, Institute of Ecology Publication No. 33, University of California, Davis; 1990; pp. 97-119.

Stockdale, E.C. and R.R. Horner. Using Freshwater Wetlands for Stormwater Management: A Progress Report. Proc. Wetlands 1988: Urban Wetlands and Riparian Habitat Symposium; Oakland, California, June 1988.

Horner, R.R. Highway Construction Site Erosion and Pollution Control: Recent Research Results. Proc. 39th Annual Road Builders' Clinic; Moscow, Idaho; March 1988; pp. 37-54.

Horner, R.R., F.B. Gutermuth, L.L. Conquest, and A.W. Johnson. Urban Stormwater and Puget Trough Wetlands. Proc. 1st Annual Meeting on Puget Sound Research; Seattle, Washington; March 1988; pp. 723-746.

Weiner, R.F., R.R. Horner, and J. Kettman. Preliminary Comparative Risk Assessment for Hanford Waste Sites. Proc. Waste Management 88; Tucson, Arizona; February 1988.

Stockdale, E.C. and R.R. Horner. Prospects for Wetlands Use in Stormwater Management. Proc. Coastal Zone 87 Conf.; Seattle, Washington; May 1987; pp. 3701-3714.

Horner, R.R. A Review of Wetland Water Quality Functions, Proc. Conf. on Wetland Functions, Rehabilitation, and Creation in the Pacific Northwest: The State of Our Understanding; Port Townsend, Washington; May 1986; pp. 33-50.

Bain, R.C., Jr., R.R. Horner, and L. Nelson. Nonpoint Pollution Control Strategies for Moses Lake, Washington. Proc. Fifth Annual Conf. North American Lake Management Society; Lake Geneva, Wisconsin; November 1985; pp. 170-176.

Shuster, J.I., E.B. Welch, R.R. Horner, and D.E. Spyridakis. Response of Lake Sammamish to Urban Runoff Control. Proc. Fifth Annual Conf. North American Lake Management Society; Lake Geneva, Wisconsin; November 1985; pp. 229-234.

Horner, R.R., J.S. Richey, and B.W. Mar. A General Approach to Designing Environmental Monitoring Programs. Proc. Pacific Section AAAS Sym. on Biomonitors, Bioindicators and Bioassays of Environmental Quality; Missoula, Montana; June 1985.

Horner, R.R. Improvement of Environmental Impact Assessment of Nonpoint Sources of Water Pollution. Proc. Non-point Pollution Abatement Sym.; Milwaukee, Wisconsin; April 1985.

Horner, R.R., E.B. Welch, M.M. Wineman, M.J. Adolfson, and R.C. Bain, Jr. Nutrient Transport Processes in an Agricultural Watershed. Proc. Fourth Annual Conf. North American Lake Management Society; McAfee, New Jersey; October 1984; pp. 221-228.

Horner, R.R. and B.W. Mar. A Predictive Model for Highway Runoff Pollutant Concentrations and Loadings. Proc. Stormwater and Water Quality Management Model Users' Group Meeting. EPA 600/9-82-015; Alexandria, Virginia; March 1982; pp. 210-224.

TECHNICAL REPORTS

Horner, R.R. Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: Flow and Water Quality Indicators and Targets. King County Water and Land Resources Division, Seattle, Washington, 2013.

Horner, R.R. and J. Gretz. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices Applied to Meet Various Potential Stormwater Runoff Regulatory Standards. Report to U.S. Environmental Protection Agency by Natural Resources Defense Council, 2011.

Horner, R.R. Section 4-2, Protection and Restoration Strategies for Watersheds and Tributaries; Chapter 4: A Science-Based Review of Ecosystem Protection and Restoration Strategies for Puget Sound and Its Watersheds; Puget Sound Science Update. Puget Sound Partnership, Tacoma, WA, 2010.

Garrison, N., R.C. Wilkinson, and R. Horner. How Greening California Cities Can Address Water Resources and Climate Challenges in the 21st Century. Natural Resources Defense Council, 2009.

Horner, R. R. Supplementary Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Francisco Bay Area. Natural Resources Defense Council, 2009.

Horner, R. R. Initial Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Francisco Bay Area. Natural Resources Defense Council, 2009.

Horner, R. R. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for Ventura County. Natural Resources Defense Council, 2008.

Horner, R. R. and C. Chapman. NW 110th Street Natural Drainage System Performance Monitoring, With Summary of Viewlands and 2nd Avenue NW SEA Streets Monitoring. Report to City of Seattle Public Utilities, 2007.

Horner, R. R. Investigation of the Feasibility and Benefits of Low-Impact Site Design Practices ("LID") for the San Diego Region. Natural Resources Defense Council, 2006.

Horner, R. R. SPU Drainage Rate Analysis Options: Recommendations on Certain Technical Issues. Report to City of Seattle Public Utilities, 2005.

Hill, K. and R. Horner. Assessment Of Alternatives In Roadside Vegetation Management. Report to Washington State Department of Transportation, 2005.

Horner, R. R. and Entranco, Inc. Regional Detention Facilities Retrofit Project: Evaluation of Regional Stormwater Ponds for Water Quality Improvements. Report to City of Bellevue Utilities Department, 2005.

Horner, R. R. and T. Osborn. Removal of Fecal Coliforms from Stormwater Runoff: A Literature Review. Report to City of Blaine, 2005.

Horner, R.R., H. Lim, and S.J. Burges. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects: Summary of the 2000-2003 Water Years, Water Resources Series Technical Report Number 181. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2004.

Horner, R.R., C.W. May, and E.H. Livingston. Linkages Between Watershed and Stream Ecosystem Conditions in Three Regions of the United States. Report to U.S. Environmental Protection Agency by Watershed Management Institute, Inc., Crawfordville, FL, 2003.

Karr, J. R., R. R. Horner, and C R. Horner. EPA's Review of Washington's Water Quality Criteria: An Evaluation of Whether Washington's Criteria Proposal Protects Stream Health and Designated Uses. Report to National Wildlife Federation, 2003.

Horner, R.R., H. Lim, and S.J. Burges. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects, Water Resources Series Technical Report Number 170. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2002.

Miller, A.V., S.B. Burges, and R.R. Horner. Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects, Water Resources Series Technical Report Number 166. Department of Civil and Environmental Engineering, University of Washington, Seattle, WA. Report to City of Seattle Public Utilities, 2001.

Mills, M. and R. R. Horner. Comprehensive Ditch and Culvert Program. Report to City of Seattle Public Utilities, 2001.

Colwell, S., R. R. Horner, D. B. Booth, and D. Gilvydis. A Survey of Ditches Along County Roads for Their Potential to Affect Storm Runoff Water Quality. Report to Snohomish County Surface Water Management Division, Snohomish County Road Maintenance, King County Land and Water Resources Division, King County Department of Transportation Road Maintenance, 2000.

Cammermayer, J. W. and R. R. Horner. Vegetated Stormwater Facility Maintenance. Report to Washington State Department of Transportation, WA-RD-495.1, 2000.

Azous, A. L. and R. R. Horner (eds.). Wetlands and Urbanization: Implications for the Future. Report to Washington Department of Ecology, 1997.

May, C. W., E. B. Welch, R. R. Horner, J. R. Karr, and B. W. Mar. Quality Indices for Urbanization Effects in Puget Sound Lowland Streams. Report to Washington Department of Ecology, 1997.

Livingston, E. H., H. E. Shaver, J. J. Skupien, and R. R. Horner. Operation, Maintenance, and Management of Stormwater Management Systems. Report to U. S. Environmental Protection Agency, 1997.

Livingston, E. H., H. E. Shaver, R. R. Horner, and J. J. Skupien,. Watershed Management Institute. Institutional Aspects of Urban Runoff Management: A Guide for Program Development and Implementation. Report to U. S. Environmental Protection Agency, 1997.

St. John, M. S. and R. R. Horner. Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity. Report to Washington State Department of Transportation, WA-RD-429.1, 1997.

Horner, R.R. Storm Drainage Water Quality Rate Basis Recommendations. Report to City of Bellevue Utilities Department, 1996.

Horner, R. R. and C. R. Horner. Impacts on Aquatic Ecosystems and Organisms of Airplane and Airport Runway Deicing Chemicals. Report to Port of Seattle, Seattle, Washington, 1996.

Horner, R. R. Constituents and Sources of Water Pollutants in Urban Stormwater Runoff. Report to Natural Resources Defense Council, Los Angeles, California, 1995.

Horner, R. R. Program Recommendations and Review of Submittals for Los Angeles County Stormwater NPDES Compliance. Report to Natural Resources Defense Council, Los Angeles, California, 1995.

Horner, R. R. and C. R. Horner. Design, Construction, and Evaluation of a Sand Filter Stormwater Treatment System, Part II, Performance Monitoring. Report to Alaska Marine Lines, Seattle, Washington, 1995.

Horner, R. R. Review of Draft Design Memorandum, Lakemont Boulevard Extension. Report to City of Bellevue, Washington, 1995.

Economic and Engineering Services, Inc. and R. R. Horner. Wetpond Restoration for Water Quality Enhancement. Report to City of Bellevue, Washington and Washington Department of Ecology, 1995.

City of Bellevue Utilities Department (R. R. Horner contributing author). Characterization and Source Control of Urban Stormwater Quality. Report to Washington Department of Ecology, 1995.

Horner, R. R. Constituents and Sources of Water Pollutants in Highway Stormwater Runoff. Report to Natural Resources Defense Council, Los Angeles, California, 1994.

Horner, R. R. Program Recommendations and Review of California Department of Transportation Submittals for Santa Monica Bay Watershed Stormwater NPDES Compliance, Support Materials. Report to Natural Resources Defense Council, Los Angeles, California, 1994.

Horner, R. R. Peer Review of Assessment of Potential Impacts from Sediment and Phosphorus Loading to Lewis Creek and Lake Sammamish - Lakemont Boulevard Extension Project. Report to City of Bellevue, Washington, 1994.

Horner, R. R. Review of the Literature on Constructed Wetlands for Municipal Wastewater Treatment. Report to Kramer, Chin and Mayo, Inc., Seattle, Washington, 1994.

Engineering Technologies Associates, Inc. and R. R. Horner. Conceptual Framework for Hydrograph Classification. Report to Water Research Center, Huntington Valley, Pennsylvania, 1994.

Horner, R. R. Phantom Lake Stormwater Controls Evaluation, Review of Water Quality Data and Literature. Report to CH2M-Hill, City of Bellevue Storm and Surface Water Utility, and Boeing Computer Services Corporation, Bellevue, Washington, 1993.

Horner, R. R. Boeing Customer Service Training Center Stormwater Quality Monitoring and Assessment Program. Report to Boeing Commercial Airplane Company, Sverdrup Corporation, and City of Renton, Washington, 1992.

Welch, E.B., R.J. Totorica and R.R. Horner. Approach to Developing Nutrient Loading Criteria for Franklin D. Roosevelt Lake. Report to Washington Department of Ecology, Olympia, 1992.

Municipality of Metropolitan Seattle (R. R. Horner contributing author). Biofiltration Swale Performance, Recommendations, and Design Considerations. Report to Washington Department of Ecology, Olympia, 1992.

Horner, R.R. and P. Kalina. Water Quality Assessment of Portage Bay. Report to City of Seattle, 1991.

Horner, R.R. and C.R. Horner. Transport and Fate of Metal and Organic Toxicants in Arid-Region Wetlands. Report to U.S. Environmental Protection Agency, Corvallis Laboratory, 1991.

King County Resource Planning Section (R. R. Horner contributing author). Development of Guidance for Managing Urban Wetlands and Stormwater. Report to Washington Department of Ecology, Olympia, 1991.

Horner, R.R. and C.R. Horner. Use of Underdrain Filter Systems for the Reduction of Stormwater Runoff Pollutants: A Literature Review. Report to Kramer, Chin and Mayo, Inc., 1990.

Reinelt, L.E. and R.R. Horner. Characterization of the Hydrology and Water Quality of Palustrine Wetlands Affected by Urban Stormwater. Report prepared for the Puget Sound Wetlands and Stormwater Management Research Program, Seattle, WA, 1990.

Horner, R. R. Analysis of Proposed Surface Water Source Control Requirements for the Commencement Bay Nearshore/Tideflats Superfund Area. Report to Port of Tacoma, Washington, 1989.

Horner, R.R. and K.J. Raedeke. Guide for Wetland Mitigation Project Monitoring. Report to Washington State Department of Transportation, 1989.

Horner, R.R., J. Guedry, and M.H. Kortenhof. Improving the Cost-Effectiveness of Highway Construction Site Erosion and Pollution Control. Report to Washington State Department of Transportation, 1989.

Horner, R.R., J. Guedry, and M.H. Kortenhof. Highway Construction Site Erosion and Pollution Control Manual. Report to Washington State Department of Transportation, 1989.

Horner, R.R., M.V. Brenner, and C.A. Jones. Design of Monitoring Programs for Determining Sources of Shellfish Bed Bacterial Contamination Problems. Report to Washington Department of Ecology, 1989.

Horner, R. R. and C. R. Horner. A Technical Review of the Sediment/Toxicant Retention and Nutrient Removal Transformation Functions of WET 2.0. Report to AScI Corporation and U. S. Environmental Protection Agency, Duluth, Minnesota, 1989.

Horner, R. R. and M. Benjamin. Washington State Pulp and Paper Plant Water Treatment Effluent Limitations. Report to Technical Resources, Inc., Rockville, Maryland, 1988.

Tetra Tech, Inc., University of Washington (R.R. Horner), and Battelle Pacific Northwest Laboratories. Recommended Protocols for Measuring Conventional Water Quality Variables and Metals in Fresh Waters of the Puget Sound Region. Report to Puget Sound Estuary Program, U.S. Environmental Protection Agency, Region 10, Seattle, 1988.

Horner, R.R. Biofiltration Systems for Storm Runoff Water Quality Control. Report to Municipality of Metropolitan Seattle, Seattle, 1988.

URS Consultants, R.R. Horner, Matrix Management Group, Weston/Northwest Cartography, and Water Resources Associates. City of Puyallup Stormwater Management Program. Report to City of Puyallup, 1988.

Welch, E.B., J. Oppenheimer, R.R. Horner, and D.E. Spyridakis. Silver Lake Water Quality Nutrient Loading and Management. Report to City of Everett, 1988.

Horner, R.R. Environmental Monitoring and Evaluation of Calcium Magnesium Acetate (CMA)--Final Report. Report to National Research Council, National Academy of Sciences, 1988.

Horner, R.R., E.B. Welch, S.R. Butkus, and D.E. Spyridakis. Management Significance of Bioavailable Phosphorus. Report to Municipality of Metropolitan Seattle and State of Washington Water Research Center, 1987.

Horner, R.R. and S.E. Cassatt. Effectiveness of Wetlands Creation in Mitigating Highway Impacts. Report to Washington State Department of Transportation, 1987.

Horner, R.R. and M.H. Kortenhof. Improving the Cost-Effectiveness of Highway Construction Site Erosion/Pollution Control, Phase 1. Report to Washington State Department of Transportation, 1987.

Horner, R.R., B.W. Mar, L.E. Reinelt, and J.S. Richey. Design of Monitoring Programs for Determination of Ecological Change Resulting from Nonpoint Source Water Pollution in Washington State. Report to Washington State Department of Ecology, 1986.

Horner, R.R., E.B. Welch, M.R. Seeley, and J.M. Jacoby. Velocity-Related Critical Phosphorus Concentrations in Flowing Water, Phase II. Report to National Science Foundation, 1986.

Horner, R.R., J.S. Richey, and D.P. Lettenmaier. Source Control of Transit Base Runoff Pollutants--Final Report. Report to Municipality of Metropolitan Seattle, 1985.

Welch, E.B., R.R. Horner, D.E. Spyridakis, and J.I. Shuster. Response of Lake Sammamish to Past and Future Phosphorus Loading. Report to Municipality of Metropolitan Seattle, 1985.

Horner, R.R. and S.R. Wonacott. Performance Evaluation of a Detention Basin and Coalescing Plate Oil Separator for Treating Urban Stormwater Runoff. Report to State of Washington Water Research Center and U.S. Geological Survey, 1985.

Cahn, D.C. and R.R. Horner. Preliminary Investigation of Sewage Sludge Utilization in Roadside Development. Report to Washington State Department of Transportation, 1985.

Horner, R.R. Highway Runoff Water Quality Research Implementation Manual, Vol. 1-2, FHWA WA-RD 72.1,2. Report to Washington State Department of Transportation, 1985.

Horner, R.R. Suggested Revisions to WSDOT Manuals for Implementing Washington State Highway Runoff Water Quality Research Results, FHWA WA-RD 72.3. Report to Washington State Department of Transportation, 1985.

Mar, B.W., D.P Lettenmaier, R.R. Horner, J.S. Richey, R.N. Palmer, S.P. Millard, and M.C. MacKenzie. Sampling Design for Aquatic Ecological Monitoring, Vol. 1-5. Final Report on Electric Power Research Institute, Project RP1729-1, 1985.

Horner, R.R., J.S. Richey, D.P. Lettenmaier, and J.F. Ferguson. Source Control of Transit Base Runoff Pollutants, Task 1--Interim Report. Report to Municipality of Metropolitan Seattle, 1984.

Brown and Caldwell Engineers and R.R. Horner. Moses Lake Clean Lake Project, Phase I. Report to Moses Lake Irrigation and Rehabilitation District, 1984.

Mar, B.W., D.P. Lettenmaier, J.S. Richey, R.R. Horner, R.N. Palmer, S.P. Millard, and G.L. Thomas. Sampling Design for Aquatic Ecological Monitoring, Phase II--Methods Development, Vol. 1-2. Report to Electric Power Research Institute, 1984.

Horner, R.R. Highway Runoff Water Quality Technology Transfer Workshop Handbook. Prepared for Washington State Department of Transportation, 1983.

Pedersen, E.R., R.R. Horner, and G.L. Portele. SR 528 - 4th Street Extension, Marysville, Snohomish County, Washington: Draft Environmental Impact Statement. Prepared for City of Marysville, 1983.

Horner, R.R., B.W. Mar, B. Chaplin, and F. Conroy. Implementation Plan for Highway Runoff Water Quality Research Results. Report to Washington State Department of Transportation, 1983.

Little, L.M., R.R. Horner, and B.W. Mar. Assessment of Pollutant Loadings and Concentrations in Highway Stormwater Runoff, FHWA WA-RD-39.17. Report to Washington State Department of Transportation, 1983.

Horner, R.R., and E.B. Welch. Velocity-Related Critical Phosphorus Concentrations in Flowing Water. Final Report to National Science Foundation for award number (CME) 79-18514, 1982.

Horner, R.R., and E.B. Welch. Impacts of Channel Reconstruction on the Pilchuck River, FHWA WA-RD-39.15. Report to Washington State Department of Transportation, 1982.

Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyridakis, and E.B. Welch. Summary - Highway Runoff Water Quality, 1977-1982, FHWA WA-RD-39.16. Report to Washington State Department of Transportation, 1982.

Horner, R.R. and B.W. Mar. Guide for Water Quality Assessment of Highway Operations and Maintenance, FHWA WA-RD-39.14. Report to Washington State Department of Transportation, 1982.

Mar, B.W., D.P. Lettenmaier, R.R. Horner, D.M. Eggers, R.N. Palmer, G.J. Portele, J.S. Richey, E.B. Welch, G. Wiens, and J. Yearsley. Sampling Design for Aquatic Ecological Monitoring, Phase 1. Report to Electric Power Research Institute, 1982.

Portele, G.J., B.W. Mar, R.R. Horner, and E.B. Welch. Effects of Seattle, Area Highway Stormwater Runoff on Aquatic Biota, FHWA WA-RD-39.11. Report to Washington State Department of Transportation, 1982.

Wang, T.S., D.E. Spyridakis, B.W. Mar, and R.R. Horner. Transport, Deposition, and Control of Heavy Metals in Highway Runoff, FHWA WA-RD-39.10. Report to Washington State Department of Transportation, 1982.

Chui, T.W., B.W. Mar, and R.R. Horner. Highway Runoff in Washington State: Model Validation and Statistical Analysis, FHWA WA-RD-39.12. Report to Washington State Department of Transportation, 1981.

Mar, B.W., J.F. Ferguson, D.E. Spyridakis, E.B. Welch, and R.R. Horner. Year 4, Runoff Water Quality, August 1980-August 1981, FHWA WA-RD-39.13. Report to Washington State Department of Transportation, 1981.

Horner, R.R. and S.M. Grason. An Ecological Study of the Monocacy Creek and its Groundwater Sources in the Vicinity of Camels Hump. Report to the Monocacy Creek Watershed Association, Bethlehem, Pennsylvania, 1981.

Horner, R.R. and E.B. Welch. Background Conditions in the Lower Pilchuck River Prior to SR-2 Construction. Report to Washington State Department of Transportation, 1979.

Horner, R.R. and B.W. Mar. Highway Runoff Monitoring: The Initial Year, FHWA WA-RD-39.3. Report to Washington State Department of Transportation, 1979.

Horner, R.R. and E.B. Welch. Effects of Velocity and Nutrient Alterations on Stream Primary Producers and Associated Organisms, FHWA WA-RD-39.2. Report to Washington State Department of Transportation, 1978.

Horner, R.R., T.J. Waddle, and S.J. Burges. Review of the Literature on Water Quality Impacts of Highway Operations and Maintenance. Report to Washington State Department of Transportation, 1977.

Horner, R.R. A Method of Defining Urban Ecosystem Relationships Through Consideration of Water Resources. U.S. Man and the Biosphere Project 11 Report, 1977.

Horner, R.R. and R. Gilliom. Bear Lake: Current Status and the Consequences of Residential Development. Report to Bear Lake Residents' Association, Kitsap County, Washington, 1977.

PRESENTATIONS AND DISCUSSIONS

*Presented by a co-author. In all other cases, I presented the paper.

Stormwater Runoff Flow Control Benefits of Urban Drainage System Reconstruction According to Natural Principles. Puget Sound/Georgia Strait Research Meeting; Vancouver, British Columbia; April 2003.

Structural and Non-Structural Best Management Practices (BMPs) for Protecting Streams. Invited presentation at the Engineering Foundation Conference on Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation; Snowmass, Colorado; August 2001.

Performance of a Perimeter ("Delaware") Sand Filter in Treating Stormwater Runoff from a Barge Loading Terminal. Invited presentation at the Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999.

Regional Study Supports Natural Land Cover Protection as Leading Best Management Practice for Maintaining Stream Ecological Integrity. Invited presentation at the Comprehensive Stormwater and Aquatic Ecosystem Management Conf.; Auckland, New Zealand; February 1999.

Watershed Determinants of Ecosystem Functioning. Invited presentation at the Engineering Foundation Conference on Effects of Watershed Development on Aquatic EcosystemsUrban Runoff and Receiving Systems; Snowbird, Utah; August 1996.

Overview of the Puget Sound Wetlands and Stormwater Management Research Program. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995.

Guidelines for Managing Urban Wetlands. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995.

Urbanization Effects on Wetland Hydrology and Water Quality. Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1995 (prepared with B. Taylor and K. Ludwa).*

Constructed Wetlands for Urban Runoff Water Quality Control. Invited presentation at National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993.

Training for Construction Site Erosion Control and Stormwater Facility Inspection. Invited presentation at National Conf. on Urban Runoff Management; Chicago, Illinois; March 1993.

Toward Ecologically Based Urban Runoff Management. Invited presentation at The Engineering Foundation Conference on Urban Runoff and Receiving Systems; Crested Butte, Colorado; August 1991.

How Stormwater Harms Shellfish. Invited presentation at the Pacific Rim Shellfish Sanitation Conference; Seattle, Washington; May 1991.

Environmental Evaluation of Calcium Magnesium Acetate for Highway Deicing Applications. Invited presentation at Conference on Calcium Magnesium Acetate, An Emerging Chemical for Environmental Applications; Boston, Massachusetts; May 1991.

Issues in Stormwater Management. Statement to State Senate Environment and Natural Resources Committee; Olympia, Washington; January 1991.

Urban Stormwater Impacts on the Hydrology and Water Quality of Palustrine Wetlands in the Puget Sound Region. Invited presentation at Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; January 1991 (prepared with L.E. Reinelt).

The Impact of Nonpoint Source Pollution on River Ecosystems. Invited presentation at the Northwest Rivers Conference; Seattle, Washington; November 1990.

Research Program Overview and Discussion of Hydrologic and Water Quality Studies. Presented at the Puget Sound Wetlands and Stormwater Management Research Program Workshop; Seattle, Washington; October 1990.

Control of Urban Runoff Water Quality. Invited presentations at American Society of Civil Engineers Urban Stormwater Short Courses; Bellevue, Washington; April, 1990; Portland, Oregon; July 1990.

Various Aspects of Erosion Prevention and Control. Invited presentations at University of Wisconsin Erosion Control Short Course; Seattle, Washington; July 1990.

Examination of the Hydrology and Water Quality of Wetlands Affected by Urban Stormwater. Presented at the Society of Wetland Scientists Annual Meeting; Breckenridge, Colorado, June 1990 (prepared with L.E. Reinelt).*

Analysis of Plant Communities of Wetlands Affected by Urban Stormwater. Presented at the Society of Wetland Scientists Annual Meeting; Breckenridge, Colorado; June 1990 (prepared with S.S. Cooke).*

Environmental Evaluation of Calcium Magnesium Acetate. Invited presentation at the Symposium on the Environmental Impact of Highway Deicing; Davis, California; October 1989.

Application of Wetland Science Principles in the Classroom and Community. Invited presentation at the Annual Meeting of the Association of Collegiate Schools of Planning; Portland, Oregon; October 1989.

Structural Controls for Urban Storm Runoff Water Quality. Invited presentation at the Northwest Regional Meeting of the North American Lake Management Society; Seattle, Washington; September 1989.

The Puget Sound Wetlands and Stormwater Management Research Program. Invited presentation at the U.S. Environmental Protection Agency Workshop on Wetlands and Stormwater; Seattle, Washington; September 1989.

An Overview of Storm Runoff Water Quality Control. Invited presentation at the American Water Resources Association Workshop on Forest Conversion; LaGrande, Washington; November 1988.

Progress in Wetlands Research. Invited presentation at the Pacific Northwest Pollution Control Association Annual Meeting; Coeur d'Alene, Idaho; October 1988.

Long-Term Effects of Urban Stormwater on Wetlands. Invited presentation at the Engineering Foundation Conference on Urban Stormwater; Potosi, Missouri; July 1988.

Highway Construction Site Erosion and Pollution Control: Recent Research Results. Invited presentation at the 39th Annual Road Builders' Clinic; Moscow, Idaho; March 1988.

Urban Stormwater and Puget Trough Wetlands. Presented at the 1st Annual Puget Sound Water Quality Authority Research Meeting; Seattle, Washington; March 1988 (prepared with F.B. Gutermuth, L.L. Conquest, and A.W. Johnson).

Preliminary Comparative Risk Assessment for Hanford Waste Sites. Presented at Waste Management 88; Tucson, Arizona; February 1988 (prepared with R.F. Weiner and J. Kettman).*

What Goes on at the Hanford Nuclear Reservation? Invited presentation at the Northwest Association for Environmental Studies Annual Meeting; Western Washington University, Bellingham, WA; November 1987.

The Puget Sound Wetlands and Stormwater Management Research Program. Invited presentation at the Pacific Northwest Pollution Control Association Annual Meeting; Spokane, Washington; October 1987.

Design of Cost-Effective Monitoring Programs for Nonpoint Source Water Pollution Problems. Invited presentation at the American Water Resources Association, Puget Sound Chapter, Annual Meeting; Bellevue, Washington; November 1986.

A Review of Wetland Water Quality Functions. Invited plenary presentation at the Conference on Wetland Functions, Rehabilitation, and Creation in the Pacific Northwest: The State of Our Understanding; Port Townsend, Washington; May 1986.

Nonpoint Discharge and Runoff session leader. American Society of Civil Engineers Spring Convention; Seattle, Washington; April 1986.

Prevention of Lake Sammamish Degradation from Future Development. Invited presentation at the American Society of Civil Engineers Spring Convention; Seattle, Washington; April 1986.

Design of Monitoring Programs for Nonpoint Source Water Pollution Problems. Invited presentation at the American Society of Civil Engineers Spring Convention; Seattle, Washington, April 1986 (prepared with L.E. Reinelt, B.W. Mar, and J.S. Richey).*

Nonpoint Pollution Control Strategies for Moses Lake, Washington. Presented at the Fifth Annual Meeting of the North American Lake Management Society; Lake Geneva, Wisconsin; November 1985 (prepared with R.C. Bain, Jr., and L. Nelson).

Response of Lake Sammamish to Urban Runoff Control. Presented at the Fifth Annual Meeting of the North American Lake Management Society; Lake Geneva, Wisconsin; November 1985 (prepared with J.I. Shuster, E.B. Welch, and D.E. Spyridakis).*

A General Approach to Designing Environmental Monitoring Programs. Invited presentation at the Pacific Section AAAS Symposium on Biomonitors, Bioindicators, and Bioassays of Environmental Quality; Missoula, Montana; June 1985 (prepared with J.S. Richey and B.W. Mar).

Panel Discussion on the Planning Process for Non-point Pollution Abatement Programs. Non-point Pollution Abatement Symposium; Milwaukee, Wisconsin; April 1985.

Nutrient Transport Processes in an Agricultural Watershed. Presented at the Fourth Annual Meeting of the North American Lake Management Society; McAfee, New Jersey; October 1984 (prepared with E.B. Welch, M.M. Wineman, M.J. Adolfson, and R.C. Bain Jr.).*

Nutrient Transport Processes in an Agricultural Watershed. Presented at the American Society of Limnology and Oceanography Annual Meeting; Vancouver, British Columbia; June 1984 (prepared with M.M. Wineman, M.J. Adolfson, and R.C. Bain, Jr.).

Factors Affecting Periphytic Algal Biomass in Six Swedish Streams. Presented at the American Society of Limnology and Oceanography Annual Meeting; Vancouver, British Columbia; June 1984 (prepared with J.M. Jacoby and E.B. Welch).*

A Conceptual Framework to Guide Aquatic Monitoring Program Design for Thermal Electric Power Plants. Presented at the American Society for Testing and Materials Symposium on Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Ecosystems; Philadelphia, Pennsylvania; November 1983 (prepared with J.S. Richey, and G.L. Thomas).

Panel Discussion. Public Forum: Perspectives on Cumulative Effects; Institute for Environmental Studies; University of Washington; Seattle, Washington; August 1983.

A Guide for Assessing the Water Quality Impacts of Highway Operations and Maintenance. Presented at the Transportation Research Board Annual Meeting; Washington, D.C.; January 1983 (prepared with B.W. Mar).

Assessment of Pollutant Loadings and Concentrations in Highway Stormwater Runoff. Presented at the Pacific Northwest Pollution Control Association Annual Meeting; Vancouver, British Columbia; November 1982 (prepared with B.W. Mar and L.M. Little).

Phosphorus and Velocity as Determinants of Nuisance Periphytic Biomass. Presented at the International Workshop on Freshwater Periphyton (SIL); Vaxjo, Sweden; September 1982 (prepared with E.B. Welch and R.B. Veenstra).*

The Development of Nuisance Periphytic Algae in Laboratory Streams in Relation to Enrichment and Velocity. Presented at the American Society of Limnology and Oceanography Annual Meeting; Raleigh, North Carolina; June 1982 (prepared with R.B. Veenstra and E.B. Welch).

A Predictive Model for Highway Runoff Pollutant Concentrations and Loadings. Presented at the Stormwater and Water Quality Model Users' Group Meeting; Alexandria, Virginia; March 1982 (prepared with B.W. Mar).

Stream Periphyton Development in Relation to Current Velocity and Nutrients. Presented at American Society of Limnology and Oceanography Winter Meeting; Corpus Christi, Texas; January 1979 (prepared with E.B. Welch).

A Comparison of Discrete Versus Composite Sampling of Storm Runoff. Presented at the Northwest Pollution Control Association Annual Meeting; Victoria, British Columbia; October 1978 (prepared with B.W. Mar and J.F. Ferguson).*

A Method of Defining Urban Ecosystem Relationships Through Consideration of Water Resources. Presented at UNESCO International Man and the Biosphere Project 11 Conference; Poznan, Poland; September 1977.

GRADUATE AND UNDERGRADUATE COURSES TAUGHT (University of Washington)

Civil and Environmental Engineering 552, Environmental Regulations; 8 quarters.

Landscape Architecture 590, Urban Water Resources Seminar; 3 quarters.

Landscape Architecture 522/523, Watershed Analysis and Design; 15 quarters.

Engineering 260, Thermodynamics; 1 quarter.

Engineering 210, Engineering Statics; 2 quarters.

Civil Engineering/Water and Air Resources 453, Water and Wastewater Treatment; 1 quarter.

Civil Engineering/Water and Air Resources 599, Analyzing Urbanizing Watersheds; 1 quarter.

CONTINUING EDUCATION SHORT COURSES TAUGHT (University of Washington; multiple offerings)

Infiltration Facilities for Stormwater Quality Control

Wetlands Ecology, Protection, and Restoration

Storm and Surface Water Monitoring

Fundamentals of Urban Surface Water Management

Applied Stormwater Pollution Prevention Planning Techniques

Construction Site Erosion and Pollution Control Problems and Planning

Construction Site Erosion and Pollution Control Practices

Construction Site Erosion and Sediment Control Inspector Training

Inspection and Maintenance of Permanent Stormwater Management Facilities

Biofiltration for Stormwater Runoff Quality Control

Constructed Wetlands for Stormwater Runoff Quality Control

LOCAL COMMITTEES

Stormwater Panel advising Puget Sound Partnership, 2007.

Technical Advisory Committee, City of Seattle Environmental Priorities Project, 1990-91.

Environmental Toxicology Graduate Program Planning Committee, University of Washington, 1990.

Habitat Modification Technical Work Group, Puget Sound Water Quality Authority, 1987.

Underground Injection Control of Stormwater Work Group, Washington State Department of Ecology, 1987.

Nonpoint Source Pollution Conference Advisory Committee, 1986-87.

Puget Sound Wetlands and Stormwater Management Research Committee, 1986-90.

Accreditation Review, University of Washington Department of Landscape Architecture, 1986.

Planning Committee for University of Washington Institute for Environmental Studies Forum on Perspectives on Cumulative Environmental Effects, 1983.

CONSULTING

Tulane Environmental Law Clinic; Assessment and declaration on a legal case involving discharge under an industrial stormwater permit; 2015.

Stillwater Science and Washington Department of Ecology; Water quality modeling for Puget Sound Characterization, Phase 2; 2010-2011.

Ventura Coastkeeper; Technical and program analysis and testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance; 2010-2015.

Earthjustice; Report and testimony regarding Washington state municipal stormwater permit before Pollution Control Hearing Board; 2008, 2013; assessment of Washington , DC combined sewer overflow control plan; 2015.

Salmon-Safe, Inc.; assessment of sites for possible certification representing practices that protect salmon; 2004-present.

Lawyers for Clean Water; Assistance with legal cases involving stormwater discharges; 2004-present.

Smith and Lowney, PLC, Seattle, Washington; Technical assistance in Clean Water Act legal cases; 1996, 2002-present.

San Diego Airport Authority; Peer review of consultant products, training; 2004-2006.

U. S. Federal Court, Central District of California; Special master in Clean Water Act case; 2001-2002.

Orange County Coastkeeper and Lawyers for Clean Water; Assistance with legal cases involving construction site pollution control and monitoring; 2001-present.

Storm Water Pollution Prevention Program, City of San Diego; Advising on response to municipal stormwater NPDES program; 2001-2002.

City of Seattle Public Utilities; Analysis of technical aspects of stormwater management program; 2000-2008.

Kerr Wood Leidel, North Vancouver, B.C.; subconsultant for Stanley Park (Vancouver, B.C.) Stormwater Constructed Wetland Design; 1997-1998.

San Diego Coastkeeper, San Diego, California; Technical and program analysis and testimony on potential legal cases involving municipal and industrial stormwater NPDES permit compliance; liaison with City of San Diego; 1996-2011.

Clean South Bay, Palo Alto, California; Technical and program analysis and testimony on potential legal cases involving municipal and industrial stormwater NPDES permit compliance; 1996.

Resource Planning Associates, Seattle, Washington; Assistance with various aspects of monitoring under Seattle-Tacoma International Airport's stormwater NPDES permit; 1995-97.

Watershed Management Institute, Crawfordsville, Florida; Writing certain chapters of guides for stormwater program development and implementation and maintenance of stormwater facilities; 1995-2003.

Natural Resources Defense Council, Los Angeles, California; Technical and program analysis and testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance; 1993-present.

Santa Monica Baykeeper (now Los Angeles Waterkeeper); Technical and program analysis and testimony on legal cases involving municipal and industrial stormwater NPDES permit compliance; 1993-present.

King County Roads Division, Seattle, Washington; Teaching two courses on construction erosion and sediment control; 1995.

Snohomish County Roads Division, Seattle, Washington; Teaching a course on construction erosion and sediment control; 1995.

Alaska Marine Lines, Seattle, Washington; Performance test of a sand filter stormwater treatment system; 1994-95.

Economic and Engineering Services, Inc., Bellevue, Washington; Assessment of the potential for water quality benefits through modifying existing stormwater ponds; technical advice on remedying operating problems at infiltration ponds; 1994-96.

Washington State Department of Transportation, Olympia, Washington; Teaching courses on construction erosion and sediment control; 1994.

City of Bellevue, Washington; Peer review of documents on potential erosion associated with a road project; analysis of stormwater quality data; 1993-95.

City of Kelowna, B. C., Canada; Teaching short courses on constructed wetlands and erosion and sediment control; 1993.

Oregon Department of Environmental Quality, Portland, Oregon; Technical review of Willamette River Basin Water Quality Study reports; 1992-93.

Whatcom County, Bellingham, Washington; Mediation on lakeshore development moratorium among county, water district, and local community representatives; 1993.

Boeing Commercial Airplane Company, Renton, Washington and Sverdrup Corporation, Kirkland, Washington (at request of City of Renton); Review of stormwater control system design; design of performance monitoring study for system; 1992-94.

Golder Associates, Redmond, Washington; Technical advisor for study of stormwater infiltration; 1992.

Smith, Smart, Hancock, Tabler, and Schwensen Attorneys, Seattle, Washington; Technical advice on a legal case involving a stormwater detention pond; 1992.

PIPE, Inc., Tacoma, Washington; Teaching a course on the stormwater NPDES permit; 1992.

CH2M-Hill, Inc., Bellevue, Washington and Portland, Oregon; Technical seminar on constructing wetlands for wastewater treatment; literature review on toxicant cycling in arid-region wetlands constructed for waterwater treatment; literature and data review on lake nutrient input reduction; expert panel on TMDL analysis for Chehalis River; 1989-1995.

Kramer, Chin and Mayo, Inc., Seattle, Washington; Watershed analysis in Washington County and Lake Oswego, Oregon; literature review in preparation for stormwater infiltration system design; literature review and contribution to design of constructed wetland for municipal wastewater treatment; 1989-1995.

Woodward-Clyde Consultants, Portland, Oregon and Oakland, California; Analysis of wetland capabilities for receiving urban stormwater; design of a constructed wetland for urban stormwater treatment; technical advisor on Washington Department of Ecology and City of Portland stormwater manual updates; 1989-1995.

R.W. Beck and Associates, Seattle, Washington; Assessment of pollutant loadings and their reduction for one master drainage planning and two watershed planning efforts; 1989-92.

Boeing Computer Services Corporation, Bellevue, Washington; mediation among Boeing, citizens' group, and City of Bellevue on stormwater control system design; 1990.

Parametrix, Inc., Bellevue, Washington; Review of Kitsap County Drainage Ordinance; 1990.

U.S. Environmental Protection Agency, Duluth Laboratory; Review of certain provisions of WET 2.0 wetland functional assessment model; 1989.

King County Council, Seattle, Washington; Review of King County Surface Water Design Manual; 1989.

Port of Tacoma, Washington; Assessment of stormwater control strategies; 1989.

Municipality of Metropolitan Seattle, Seattle, Washington; Assessment of land treatment systems for controlling urban storm runoff water quality; 1988-1992.

Impact Assessment, Inc., La Jolla, California (contractor to Washington State Department of Ecology); Socioeconomic impact assessment of the proposed high-level nuclear waste repository at Hanford, Washington; 1987.

Technical Resources, Inc., Rockville, Maryland (contractor to U. S. Environmental Protection Agency); assessment of water treatment waste disposal at pulp and paper plants; 1987-88.

Dames and Moore, Seattle, Washington; analysis of the consequences of a development to Martha Lake; 1987.

Harper-Owes, Seattle, Washington; project oversight, data analysis, and review of limnological aspects for Lake Chelan Water Quality Assessment Study; 1986-88.

URS Corporation, Seattle, Washington and Columbus, Ohio; presentation of a workshop on nonpoint source water pollution monitoring program design; analysis of innovative and alternative wastewater treatment for Columbus; development of a stormwater utility for Puyallup, Washington; watershed analysis for Edmonds, Washington; 1986-88.

Entranco Engineers, Bellevue, Washington; environmental impact assessment of proposed highway construction; technical review of Lake Sammamish watershed management project; technical review of Capital Lake wetland development; 1981-82; 1987-88; 1990.

Washington State Department of Ecology, Olympia, Washington; review of literature on wetland water quality, preparation of conference plenary paper, and leading discussion group at conference; analysis in preparation for a Shoreline Hearing Board case; 1986-87.

Richard C. Bain, Jr., Engineering Consultant, Vashon Island, Washington; analysis of watershed data and development of a policy for septic tank usage near Moses Lake, Washington; 1984-87.

University of Washington Friday Harbor Laboratory; analysis of adjacent port development and preparation of testimony for Shoreline Hearing Board; 1986.

Washington State Department of Transportation and Morrison-Knudsen Company, Inc./H.W. Lochner, Inc., Joint Venture, Mercer Island, Washington; environmental assessment of disposal of excavated material by capping a marine dredge spoil dumping site; 1984.

Foster, Pepper, and Riviera Attorneys, Seattle, Washington; analysis and testimony on provisions to reduce pollutants in stormwater runoff from a site proposed for development; 1983.

Williams, Lanza, Kastner, and Gibbs Attorneys, Seattle, Washington; collection and analysis of water quality data to support a legal case and preparation of testimony; 1982.

Herrera Environmental Consultants, Seattle, Washington; lake data analysis and report preparation; 1982-83.

Brown and Caldwell Engineers, Seattle, Washington; data collection and analysis for watershed study; 1982-83.

City of Marysville, Washington; environmental impact assessment of proposed bridge construction; 1982-83.

F.X. Browne Associates, Inc., Lansdale, Pennsylvania; contributions to manual on lake restoration for U.S. Environmental Protection Agency; preparation of funding proposals and permits for lake restoration; lake data analysis; literature reviews and analysis of septic tank contributions to lake nutrient loading and availability of different forms of nutrients; 1980-83.

Reston Division of Prentice-Hall, Inc., Reston, Virginia; review of and contributions to texts on environmental technology; 1978-79.

Butterfield, Joachim, Brodt, and Hemphill Attorneys, Bethlehem, Pennsylvania; analysis of environmental impact statements; expert witness; 1973.

ATTACHMENT C

COUNTY OF SAN DIEGO BMP DESIGN MANUAL

Appendix

D

Approved Infiltration Rate Assessment Methods for Selection of Storm Water BMPs

February 26, 2016

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Appendix D Approved Infiltration Rate Assessment Methods for Selection and Design of Storm Water BMPs

D.1 Introduction

Characterization of potential infiltration rates is a critical step in evaluating the degree to which infiltration can be used to reduce storm water runoff volume. This appendix is intended to provide guidance to help answer the following questions:

1. *How and where does infiltration testing fit into the project development process?*

   Section D.2 discusses the role of infiltration testing in different stage of project development and how to plan a phased investigation approach.

2. *What infiltration rate assessment methods are acceptable?*

   Section D.3 describes the infiltration rate assessment methods that are acceptable.

3. *What factors should be considered in selecting the most appropriate testing method for a project?*

   Section D.4 provides guidance on site-specific considerations that influence which assessment methods are most appropriate.

4. *How should factors of safety be selected and applied to, for BMP selection and design?*

   Section D.5 provides guidance for selecting a safety factor.

Note, that this appendix does not consider other feasibility criteria that may make infiltration infeasible, such as groundwater contamination and geotechnical considerations (these are covered in Appendix C). In general, infiltration testing should only be conducted after other feasibility criteria specified in this manual have been evaluated and cleared.

D.2 Role of Infiltration Testing in Different Stages of Project Development

In the process of planning and designing infiltration facilities, there are a number of ways that infiltration testing or estimation factors into project development, as summarized in Table D.2-1. As part of selecting infiltration testing methods, the geotechnical engineer must select methods that are applicable to the phase of the project and the associated burden of proof.

Table D.2-1: Role of Infiltration Testing

Project Phase	Key Questions/Burden of Proof	General Assessment Strategies
Site Planning Phase	• Where within the project area is infiltration potentially feasible? • What volume reduction approaches are potentially suitable for my project?	• Use existing data and maps to the extent possible • Use less expensive methods to allow a broader area to be investigated more rapidly • Reach tentative conclusions that are subject to confirmation/refinement at the design phase
BMP Design Phase	• What infiltration rates should be used to design infiltration and biofiltration facilities? • What factor of safety should be applied?	• Use more rigorous testing methods at specific BMP locations • Support or modify preliminary feasibility findings • Estimate design infiltration rates with appropriate factors of safety

D.3 Guidance for Selecting Infiltration Testing Methods

The geotechnical engineer must select appropriate testing methods for the site conditions, subject to the engineer's discretion and approval of the County, that are adequate to meet the burden of proof that is applicable at each phase of the project design (See Table D.3-1):

- At the planning phase, testing/evaluation method must be selected to provide a reliable estimate of the locations where infiltration is feasible and allow a reasonably confident determination of infiltration feasibilility to support the selection between full infiltration, partial infiltration, and no infiltration BMPs.

- At the design phase, the testing method must be selected to provide a reliable infiltration rate to be used in design. The degree of certainty provided by the selected test should be considered

Table D.3-1 provides a matrix comparison of these methods. Sections D.3.1 to D.3.3 provide a summary of each method. This appendix is not intended to be an exhaustive reference on infiltration testing at this time. It does not attempt to discuss every method for testing, nor is it intended to provide step-by-step procedures for each method. The user is directed to supplemental resources (referenced in this appendix) or other appropriate references for more specific information. **Alternative testing methods are allowed with appropriate rationales, subject to the discretion of the County.**

In order to select an infiltration testing method, it is important to understand how each test is applied and what specific physical properties the test is designed to measure. Infiltration testing methods vary considerably in these regards. For example, a borehole percolation test is conducted by drilling a borehole, filling a portion of the hole with water, and monitoring the rate of fall of the water. This test directly measures the three dimensional flux of water into the walls and bottom of the borehole. An approximate correction is applied to indirectly estimate the vertical hydraulic conductivity from the results of the borehole test. In contrast, a double-ring infiltrometer test is conducted from the ground surface and is intended to provide a direct estimate of vertical (one-dimensional) infiltration rate at this point. Both of these methods are applicable under different conditions.

Table D.3-1: Comparision of Infiltration Rate Estimation and Testing Methods

Test	Suitability at Planning Level Screening Phase	Suitability at BMP Design Phase
NRCS Soil Survey Maps	Yes, but mapped soil types must be confirmed with site observations. Regional soil maps are known to contain inaccuracies at the scale of typical development sites.	No, unless a strong correlation is developed between soil types and infiltration rates in the direct vicinity of the site and an elevated factor of safety is used.
Grain Size Analysis	Not preferred. Should only be used if a strong correlation has been developed between grain size analysis and measured infiltration rates testing results of site soils.	No
Cone Penetrometer Testing	Not preferred. Should only be used if a strong correlation has been developed between CPT results and measured infiltration rates testing results of site soils.	No
Simple Open Pit Test	Yes	Yes, with appropriate correction for infiltration into side walls and elevated factor of safety.
Open Pit Falling Head Test	Yes	Yes, with appropriate correction for infiltration into side walls and elevated factor of safety.
Double Ring Infiltrometer Test (ASTM 3385)	Yes	Yes

Test	Suitability at Planning Level Screening Phase	Suitability at BMP Design Phase
Single Ring Infiltrometer Test	Yes	Yes
Large-scale Pilot Infiltration Test	Yes, but generally cost prohibitive and too water-intensive for preliminary screening of a large area.	Yes, but should consider relatively large water demand associated with this test.
Smaller-scale Pilot Infiltration Test	Yes	Yes
Well Permeameter Method (USBR 7300-89)	Yes; reliability of this test can be improved by obtaining a continuous core where tests are conducted.	Yes in areas of proposed cut where other tests are not possible; a continuous boring log should be recorded and used to interpret test; should be confirmed with a more direct measurement following excavation.
Borehole Percolation Tests (various methods)	Yes; reliability of this test can be improved by obtaining a continuous core where tests are conducted.	Yes in areas of proposed cut where other tests are not possible; a continuous boring log should be recorded and used to interpret test; should be confirmed with a more direct measurement following excavation.
Laboratory Permeability Tests (e.g., ASTM D2434)	Yes, only suitable for evaluating potential infiltration rates in proposed fill areas. For sites with proposed cut, it is preferred to do a borehole percolation test at the proposed grade instead of analyzing samples in the lab. A combination of both tests may improve reliability.	No. However, may be part of a line of evidence for estimating the design infiltration of partial infiltration BMPs constructed in future compacted fill.

D.3.1 Desktop Approaches and Data Correlation Methods

This section reviews common methods used to evaluate infiltration characteristics based on desktop-available information, such as GIS data. This section also introduces methods for estimating infiltration properties via correlations with other measurements.

D.3.1.1 NRCS Soil Survey Maps

NRCS Soil Survey maps (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) can be used to estimate preliminary feasibility conditions, specifically by mapping hydrologic soil groups, soil texture classes, and presence of hydric soils relative to the site layout. For feasibility determinations, mapped conditions must be supplemented with available data from the site (e.g., soil borings, observed soil textures, biological indicators). The presence of D soils, if confirmed by available data, provides a reasonable basis to determine that full infiltration is not feasible for a given DMA.

D.3.1.2 Grain Size Analysis Testing and Correlations to Infiltration Rate

Hydraulic conductivity can be estimated indirectly from correlations with soil grain-size distributions. While this method is approximate, correlations have been relatively well established for some soil conditions. One of the most commonly used correlations between grain size parameters and hydraulic conductivity is the Hazen (1892, 1911) empirical formula (Philips and Kitch, 2011), but a variety of others have been developed. Correlations must be developed based on testing of site-specific soils.

D.3.1.3 Cone Penetrometer Testing and Correlations to Infiltration Rate

Hydraulic conductivity can also be estimated indirectly from cone penetrometer testing (CPT). A cone penetrometer test involves advancing a small probe into the soil and measuring the relative resistance encountered by the probe as it is advanced. The signal returned from this test can be interpreted to yield estimated soil types and the location of key transitions between soil layers. If this method is used, correlations must be developed based on testing of site-specific soils.

D.3.2 Surface and Shallow Excavation Methods

This section describes tests that are conducted at the ground surface or within shallow excavations close to the ground surface. These tests are generally applicable for cases where the bottom of the infiltration system will be near the existing ground surface. They can also be conducted to confirm the results of borehole methods after excavation/site grading has been completed.

D.3.2.1 Simple Open Pit Test

The Simple Open Pit Test is most appropriate for planning level screening of infiltration feasibility. Although it is similar to Open Pit Falling Head tests used for establishing a design infiltration rate (see below), the Simple Open Pit Test is less rigorous and is generally conducted to a lower standard of care. This test can be conducted by a nonprofessional as part of planning level screening phase.

The Simple Open Pit Test is a falling head test in which a hole at least two feet in diameter is filled with water to a level of 6" above the bottom. Water level is checked and recorded regularly until either an hour has passed or the entire volume has infiltrated. The test is repeated two more times in succession and the rate at which the water level falls in the third test is used as the infiltration rate.

This test has the advantage of being inexpensive to conduct. Yet it is believed to be fairly reliable for screening as the dimensions of the test are similar, proportionally, to the dimensions of a typical BMP. The key limitations of this test are that it measures a relatively small area, does not necessarily result in a precise measurement, and may not be uniformly implemented.

Source: City of Portland, 2008. Storm Water Management Manual

D.3.2.2 Open Pit Falling Head Test

This test is similar to the Simple Open Pit Test, but covers a larger footprint, includes more specific instructions, returns more precise measurements, and generally should be overseen by a geotechnical professional. Nonetheless, it remains a relatively simple test.

To perform this test, a hole is excavated at least 2 feet wide by 4 feet long (larger is preferred) and to a depth of at least 12 inches. The bottom of the hole should be approximately at the depth of the proposed infiltrating surface of the BMP. The hole is pre-soaked by filling it with water at least a foot above the soil to be tested and leaving it at least 4 hours (or overnight if clays are present). After pre-soaking, the hole is refilled to a depth of 12 inches and allow it to drain for one hour (2 hours for slower soils), measuring the rate at which the water level drops. The test is then repeated until successive trials yield a result with less than 10 percent change.

In comparison to a double-ring infiltrometer, this test has the advantage of measuring infiltration over a larger area and better resembles the dimensionality of a typical small scale BMP. Because it includes both vertical and lateral infiltration, it should be adjusted to estimate design rates for larger scale BMPs.

D.3.2.3 Double Ring Infiltrometer Test (ASTM 3385)

The Double Ring Infiltrometer was originally developed to estimate the saturated hydraulic conductivity of low permeability materials, such as clay liners for ponds, but has seen significant use in storm water applications. The most recent revision of this method from 2009 is known as ASTM 3385-09. The testing apparatus is designed with concentric rings that form an inner ring and an annulus between the inner and outer rings. Infiltration from the annulus between the two rings is intended to saturate the soil outside of the inner ring such that infiltration from the inner ring is restricted primarily to the vertical direction.

To conduct this test, both the center ring and annulus between the rings are filled with water. There is no pre-wetting of the soil in this test. However, a constant head of 1 to 6 inches is maintained for 6 hours, or until a constant flow rate is established. Both the inner flow rate and annular flow rate are recorded, but if they are different, the inner flow rate should be used. There are a variety of approaches that are used to maintain a constant head on the system, including use of a Mariotte tube, constant level float valves, or manual observation and filling. This test must be conducted at the elevation of the proposed infiltrating surface; therefore application of this test is limited in cases where the infiltration surface is a significant distance below existing grade at the time of testing.

This test is generally considered to provide a direct estimate of vertical infiltration rate for the specific point tested and is highly replicable. However, given the small diameter of the inner ring (standard diameter is 12 inches, but it can be larger), this test only measures infiltration rate in a small area. Additionally, given the small quantity of water used in this test compared to larger scale tests, this test may be biased high in cases where the long term infiltration rate is governed by groundwater mounding and the rate at which mounding dissipates (i.e., the capacity of the infiltration receptor). Finally, the added effort and cost of isolating vertical infiltration rate may not necessarily be warranted considering that BMPs typically have a lateral component of infiltration as well. Therefore, while this method has the advantages of being technical rigorous and well standardized, it should not necessarily be assumed to be the most representative test for estimating full-scale infiltration rates. Source: American Society for Testing and Materials (ASTM) International (2009)

D.3.2.4 Single Ring Infiltrometer Test

The single ring infiltrometer test is not a standardized ASTM test, however it is a relatively well-controlled test and shares many similarities with the ASTM standard double ring infiltrometer test (ASTM 3385-09). This test is a constant head test using a large ring (preferably greater than 40 inches in diameter) usually driven 12 inches into the soil. Water is ponded above the surface. The rate of water addition is recorded and infiltration rate is determined after the flow rate has stabilized. Water can be added either manually or automatically.

The single ring used in this test tends to be larger than the inner ring used in the double ring test. Driving the ring into the ground limits lateral infiltration; however some lateral infiltration is generally considered to occur. Experience in Riverside County (CA) has shown that this test gives results that are close to full-scale infiltration facilities. The primary advantages of this test are that it is relatively simple to conduct and has a larger footprint (compared to the double-ring method) and restricts horizontal infiltration and is more standardized (compared to open pit methods). However, it is still a relatively small scale test and can only be reasonably conducted near the existing ground surface.

D.3.2.5 Large-scale Pilot Infiltration Test

As its name implies, this test is closer in scale to a full-scale infiltration facility. This test was developed by Washington State Department of Ecology specifically for storm water applications.

To perform this test, a test pit is excavated with a horizontal surface area of roughly 100 square feet to a depth that allows 3 to 4 feet of ponding above the expected bottom of the infiltration facility. Water is continually pumped into the system to maintain a constant water level (between 3 and 4 feet about the bottom of the pit, but not more than the estimated water depth in the proposed facility) and the flow rate is recorded. The test is continued until the flow rate stabilizes. Infiltration rate is calculated by dividing the flow rate by the surface area of the pit. Similar to other open pit test, this test is known to result in a slight bias high because infiltration also moves laterally through the walls of the pit during the test. Washington State Department of Ecology requires a correction factor of 0.75 (factor of safety of 1.33) be applied to results.

This test has the advantage of being more resistant to bias from localized soil variability and being more similar to the dimensionality and scale of full scale BMPs. It is also more likely to detect long term decline in infiltration rates associated with groundwater mounding. As such, it remains the preferred test for establishing design infiltration rates in Western Washington (Washington State Department of Ecology, 2012). In a comparative evaluation of test methods, this method was found to provide a more reliable estimate of full-scale infiltration rate than double ring infiltrometer and borehole percolation tests (Philips and Kitch 2011).

The difficulty encountered in this method is that it requires a larger area be excavated than the other methods, and this in turn requires larger equipment for excavation and a greater supply of water. However, this method should be strongly considered when less information is known about spatial variability of soils and/or a higher degree of certainty in estimated infiltration rates is desired.

Source: Washington State Department of Ecology, 2012.

D.3.2.6 Smaller-scale Pilot Infiltration Test

The smaller-scale PIT is conducted similarly to the large-scale PIT but involves a smaller excavation, ranging from 20 to 32 square feet instead of 100 square feet for the large-scale PIT, with similar depths. The primary advantage of this test compared to the full-scale PIT is that it requires less excavation volume and less water. It may be more suitable for small-scale distributed infiltration controls where the need to conduct a greater number of tests outweighs the accuracy that must be obtained in each test, and where groundwater mounding is not as likely to be an issue. Washington State Department of Ecology establishes a correction factor of 0.5 (factor of safety of 2.0) for this test in comparison to 0.75 (factor of safety of 1.33) for the large-scale PIT to account for a greater fraction of water infiltrating through the walls of the excavation and lower degree of certainty related to spatial variability of soils.

D.3.3 Deeper Subsurface Tests

D.3.3.1 Well Permeameter Method (USBR 7300-89)

Well permeameter methods were originally developed for purposes of assessing aquifer permeability and associated yield of drinking water wells. This family of tests is most applicable in situations in which infiltration facilities will be placed substantially below existing grade, which limits the use of surface testing methods.

In general, this test involves drilling a 6 inch to 8 inch test well to the depth of interest and maintaining a constant head until a constant flow rate has been achieved. Water level is maintained with down-hole floats. The Porchet method or the nomographs provided in the USBR Drainage Manual (United States Department of the Interior, Bureau of Reclamation, 1993) are used to convert the measured rate of percolation to an estimate of vertical hydraulic conductivity. A smaller diameter boring may be adequate, however this then requires a different correction factor to account for the increased variability expected.

While these tests have applicability in screening level analysis, considerable uncertainty is introduced in the step of converting direct percolation measurements to estimates of vertical infiltration. Additionally, this testing method is prone to yielding erroneous results cases where the vertical horizon of the test intersects with minor lenses of sandy soils that allow water to dissipate laterally at a much greater rate than would be expected in a full-scale facility. To improve the interpretation of this test method, a continuous bore log should be inspected to determine whether thin lenses of material may be biasing results at the strata where testing is conducted. Consult USBR procedure 7300-89 for more details.

Source: (United States Department of the Interior, Bureau of Reclamation, 1990, 1993)

D.3.3.2 Borehole Percolation Tests (various methods)

Borehole percolation tests were originally developed as empirical tests to estimate the capacity of onsite sewage disposal systems (septic system leach fields), but have more recently been adopted into use for evaluating storm water infiltration. Similar to the well permeameter method, borehole percolation methods primarily measure lateral infiltration into the walls of the boring and are designed for situations in which infiltration facilities will be placed well below current grade. The percolation rate obtained in this test should be converted to an infiltration rate using a technique such as the Porchet method.

This test is generally implemented similarly to the USBR Well Permeameter Method. Per the Riverside County Borehole Percolation method, a hole is bored to a depth at least 5 times the borehole radius. The hole is presoaked for 24 hours (or at least 2 hours if sandy soils with no clay). The hole is filled to approximately the anticipated top of the proposed infiltration basin. Rates of fall are measured for six hours, refilling each half hour (or 10 minutes for sand). Tests are generally repeated until consistent results are obtained.

The same limitations described for the well permeameter method apply to borehole percolation tests, and their applicability is generally limited to initial screening. To improve the interpretation of this test method, a continuous soil core can be extracted from the hole and below the test depth, following testing, to determine whether thin lenses of material may be biasing results at the strata where testing is conducted.

Sources: Riverside County Percolation Test (2011), California Test 750 (Caltrans, 1986), San Bernardino County Percolation Test (1992); USEPA Falling Head Test (USEPA, 1980).

D.4 Specific Considerations for Infiltration Testing

The following subsections are intended to address specific topics that commonly arise in characterizing infiltration rates.

D.4.1 Hydraulic Conductivity versus Infiltration Rate versus Percolation Rate

A common misunderstanding is that the "percolation rate" obtained from a percolation test is equivalent to the "infiltration rate" obtained from tests such as a single or double ring infiltrometer test which is equivalent to the "saturated hydraulic conductivity". In fact, these terms have different meanings. Saturated hydraulic conductivity is an intrinsic property of a specific soil sample under a given degree of compaction. It is a coefficient in Darcy's equation (Darcy 1856) that characterizes the flux of water that will occur under a given gradient. The measurement of saturated hydraulic conductivity in a laboratory test is typically referred to as "permeability", which is a function of the density, structure, stratification, fines, and discontinuities of a given sample under given controlled conditions. In contrast, infiltration rate is an empirical observation of the rate of flux of water into a given soil structure under long term ponding conditions. Similarly to permeability, infiltration rate can be limited by a number of factors including the layering of soil, density, discontinuities, and initial moisture content. These factors control how quickly water can move through a soil. However, infiltration rate can also be influenced by mounding of groundwater, and the rate at which water dissipates horizontally below a BMP – both of which describe the "capacity" of the "infiltration receptor" to accept this water over an extended period. For this reason, an infiltration test should ideally be conducted for a relatively long duration resembling a series of storm events so that the capacity of the infiltration receptor is evaluated as well as the rate at which water can enter the system. Infiltration rates are generally tested with larger diameter holes, pits, or apparatuses intended to enforce a primarily vertical direction of flux.

In contrast, percolation is tested with small diameter holes, and it is mostly a lateral phenomenon. The direct measurement yielded by a percolation test tends to overestimate the infiltration rate, except perhaps in cases in which a BMP has similar dimensionality to the borehole, such as a dry well. Adjustment of percolation rates may be made to an infiltration rate using a technique such as the Porchet Method.

D.4.2 Cut and Fill Conditions

Cut Conditions: Where the proposed infiltration BMP is to be located in a cut condition, the infiltration surface level at the bottom of the BMP might be far below the existing grade. For example, if the infiltration surface of a proposed BMP is to be located at an elevation that is currently beneath 15 feet of planned cut, ***how can the proposed infiltration surface be tested to establish a design infiltration rate prior to beginning excavation?*** The question can be addressed in two ways: First, one of the deeper subsurface tests described above can be used to provide a planning level screening of potential rates at the elevation of the proposed infiltrating surface. These tests can be conducted at depths exceeding 100 feet, therefore are applicable in most cut conditions. Second, the project can commit to further testing using more reliable methods following bulk excavation to refine or adjust infiltration rates, and/or apply higher factors of safety to borehole methods to account for the inherent uncertainty in these measurements and conversions.

Fill Conditions: There are two types of fills – those that are engineered or documented, and those that are undocumented. Undocumented fills are fills placed without engineering controls or construction quality assurance and are subject to great uncertainty. Engineered fills are generally placed using construction quality assurance procedures and may have criteria for grain-size and fines content, and the properties can be very well understood. However, for engineered fills, infiltration rates may still be quite uncertain due to layering and heterogeneities introduced as part of construction that cannot be precisely controlled.

If the bottom of a BMP (infiltration surface) is proposed to be located in a fill location, the infiltration surface may not exist prior to grading. How then can the infiltration rate be determined? For example, if a proposed infiltration BMP is to be located with its bottom elevation in 10 feet of fill, how could one reasonably establish an infiltration rate prior to the fill being placed?

Where possible, infiltration BMPs on fill material should be designed such that their infiltrating surface extends into native soils. Additionally, for shallow fill depths, fill material can be selectively graded (i.e., high permeability granular material placed below proposed BMPs) to provide reliable infiltration properties until the infiltrating water reaches native soils. In some cases, due to considerable fill depth, the extension of the BMP down to natural soil and/or selective grading of fill material may prove infeasible. In addition, fill material will result in some compaction of now buried native soils potentially reducing their ability to infiltrate. In these cases, because of the uncertainty of fill parameters as described above as well as potential compaction of the native soils, an infiltration BMP may not be feasible.

If the source of fill material is defined and this material is known to be of a granular nature and that the native soils below is permeable and will not be highly compacted, infiltration through compacted fill materials may still be feasible. In this case, a project phasing approach could be used including the following general steps, (1) collect samples from areas expected to be used as borrow sites for fill activities, (2) remold samples to approximately the proposed degree of compaction and measure the saturated hydraulic conductivity of remolded samples using laboratory methods, (3) if infiltration rates appear adequate for infiltration, then apply an appropriate factor of safety and use the initial rates for preliminary design, (4) following placement of fill, conduct in-situ testing to refine design infiltration rates and adjust the design as needed; the infiltration rate of native soil below the fill should also be tested at this time to determine if compaction as a result of fill placement has significantly reduced its infiltration rate. The project geotechnical engineer should be involved in decision making whenever infiltration is proposed in the vicinity of engineered fill structures so that potential impacts of infiltration on the strength and stability of fills and pavement structures can be evaluated.

D.4.3 Effects of Direct and Incidental Compaction

It is widely recognized that compaction of soil has a major influence on infiltration rates (Pitt et al. 2008). However, direct (intentional) compaction is an essential aspect of project construction and indirect compaction (such as by movement of machinery, placement of fill, stockpiling of materials, and foot traffic) can be difficult to avoid in some parts of the project site. Infiltration testing strategies should attempt to measure soils at a degree of compaction that resembles anticipated post-construction conditions.

Ideally, infiltration systems should be located outside of areas where direct compaction will be required and should be staked off to minimize incidental compaction from vehicles and stockpiling. For these conditions, no adjustment of test results is needed.

However, in some cases, infiltration BMPs will be constructed in areas to be compacted. For these areas, it may be appropriate to include field compaction tests or prepare laboratory samples and conducting infiltration testing to approximate the degree of compaction that will occur in post-construction conditions. Alternatively, testing could be conducted on undisturbed soil, and an additional factor of safety could be applied to account for anticipated infiltration after compaction. To develop a factor of safety associated with incidental compaction, samples could compacted to various degrees of compaction, their hydraulic conductivity measured, and a "response curve" developed to relate the degree of compaction to the hydraulic conductivity of the material.

D.4.4 Temperature Effects on Infiltration Rate

The rate of infiltration through soil is affected by the viscosity of water, which in turn is affected by the temperature of water. As such, infiltration rate is strongly dependent on the temperature of the infiltrating water (Cedergren, 1997). For example, Emerson (2008) found that wintertime infiltration rates below a BMP in Pennsylvania were approximately half their peak summertime rates. As such, it is important to consider the effects of temperature when planning tests and interpreting results.

If possible, testing should be conducted at a temperature that approximates the typical runoff temperatures for the site during the times when rainfall occurs. If this is not possible, then the results of infiltration tests should be adjusted to account for the difference between the temperature at the time of testing and the typical temperature of runoff when rainfall occurs. The measured infiltration can be adjusted by the ratio of the viscosity at the test temperature versus the typical temperature when rainfall occurs (Cedergren, 1997), per the following formula:

$$K_{Typical} = K_{Test} \times \left(\frac{\mu_{Test}}{\mu_{Typical}} \right)$$

Where:

$K_{Typical}$ = the typical infiltration rate expected at typical temperatures when rainfall occurs
K_{Test} = the infiltration rate measured or estimated under the conditions of the test
$\mu_{Typical}$ = the viscosity of water at the typical temperature expected when rainfall occurs
μ_{Test} = the viscosity of water at the temperature at which the test was conducted

D.4.5 Number of Infiltration Tests Needed

The heterogeneity inherent in soils implies that all but the smallest proposed infiltration facilities would benefit from infiltration tests in multiple locations. The following requirements apply for in situ infiltration/percolation testing:

- In situ infiltration/ percolation testing must be conducted at a minimum of two locations within 50-feet of each proposed storm water infiltration/ percolation BMP.
- In situ infiltration/percolation testing must be conducted using an approved method listed in Table D.3-1
- Testing must be conducted at approximately the same depth and in the same material as the base of the proposed storm water BMP.

D.5 Selecting a Safety Factor

Should I use a factor of safety for design infiltration rate?

Monitoring of actual facility performance has shown that the full-scale infiltration rate can be much lower than the rate measured by small-scale testing (King County Department of Natural Resources and Parks, 2009). Factors such as soil variability and groundwater mounding may be responsible for much of this difference. Additionally, the infiltration rate of BMPs naturally declines between maintenance cycles as the BMP surface becomes occluded and particulates accumulate in the infiltrative layer.

In the past, infiltration structures have been shown to have a relatively short lifespan. Over 50 percent of infiltration systems either partially or completely failed within the first 5 years of operation (United States EPA. 1999). In a Maryland study on infiltration trenches (Lindsey et al. 1991), 53 percent were not operating as designed, 36 percent were clogged, and 22 percent showed reduced filtration. In a study of 12 infiltration basins (Galli 1992), none of which had built-in pretreatment systems, all had failed within the first two years of operation.

Given the known potential for infiltration BMPs to degrade or fail over time, an appropriate factor of safety applied to infiltration testing results is strongly recommended. This section presents a recommended thought process for selecting a safety factor. This method considers factor of safety to be a function of:

- Site suitability considerations, and
- Design-related considerations.

These factors and the method for using them to compute a safety factor are discussed below. Importantly, this method encourages rigorous site investigation, good pretreatment, and commitments to routine maintenance to provide technically-sound justification for using a lower factor of safety.

D.5.1 Determining Factor of Safety

Worksheet D.5-1, at the end of this section can be used in conjunction with Tables D.5-1 and D.5-2 to determine an appropriate safety factor. Tables D.5-1 and D.5-2 assign point values to design considerations; the values are entered into Worksheet D.5-1, which assign a weighting factor for each design consideration.

The following procedure can be used to estimate an appropriate factor of safety to be applied to the infiltration testing results. When assigning a factor of safety, care should be taken to understand what other factors of safety are implicit in other aspects of the design to avoid incorporating compounding factors of safety that may result in significant over-design.

1. For each consideration shown above, determine whether the consideration is a high, medium, or low concern.
2. For all high concerns in Table D.5-1, assign a factor value of 3, for medium concerns, assign a factor value of 2, and for low concerns assign a factor value of 1.
3. Multiply each of the factors in Table D.5-1 by 0.25 and then add them together. This should yield a number between 1 and 3.
4. For all high concerns in Table D.5-2, assign a factor value of 3, for medium concerns, assign a factor value of 2, and for low concerns assign a factor value of 1.
5. Multiply each of the factors in Table D.5-2 by 0.5 and then add them together. This should yield a number between 1 and 3.
6. Multiply the two safety factors together to get the final combined safety factor. If the combined safety factor is less than 2, then 2 should be used as the safety factor.
7. Divide the tested infiltration rate by the combined safety factor to obtain the adjusted design infiltration rate for use in sizing the infiltration facility.

Note: The minimum combined adjustment factor should not be less than 2.0 and the maximum combined adjustment factor should not exceed 9.0.

D.5.2 Site Suitability Considerations for Selection of an Infiltration Factor of Safety

Considerations related to site suitability include:

- Soil assessment methods – the site assessment extent (e.g., number of borings, test pits, etc.) and the measurement method used to estimate the short-term infiltration rate.
- Predominant soil texture/percent fines – soil texture and the percent of fines can influence the potential for clogging. Finer grained soils may be more susceptible to clogging.
- Site soil variability – site with spatially heterogeneous soils (vertically or horizontally) as determined from site investigations are more difficult to estimate average properties for resulting in a higher level of uncertainty associated with initial estimates.
- Depth to seasonal high groundwater/impervious layer – groundwater mounding may become an issue during excessively wet conditions where shallow aquifers or shallow clay lenses are present.

These considerations are summarized in Table D.5-1 below, in addition to presenting classification of concern.

Table D.5-1: Suitability Assessment Related Considerations for Infiltration Facility Safety Factors

Appendix D: Approved Infiltration Rate Assessment Methods

Consideration	High Concern – 3 points	Medium Concern – 2 points	Low Concern – 1 point
Assessment methods (see explanation below)	Use of soil survey maps or simple texture analysis to estimate short-term infiltration rates Use of well permeameter or borehole methods without accompanying continuous boring log Relatively sparse testing with direct infiltration methods	Use of well permeameter or borehole methods with accompanying continuous boring log Direct measurement of infiltration area with localized infiltration measurement methods (e.g., infiltrometer) Moderate spatial resolution	Direct measurement with localized (i.e., small-scale) infiltration testing methods at relatively high resolution[1] or Use of extensive test pit infiltration measurement methods[2]
Texture Class	Silty and clayey soils with significant fines	Loamy soils	Granular to slightly loamy soils
Site soil variability	Highly variable soils indicated from site assessment, or Unknown variability	Soil borings/test pits indicate moderately homogeneous soils	Soil borings/test pits indicate relatively homogeneous soils
Depth to groundwater/ impervious layer	<5 ft below facility bottom	5-15 ft below facility bottom	>15 below facility bottom

1 - Localized (i.e., small scale) testing refers to methods such as the double-ring infiltrometer and borehole tests)

2 - Extensive infiltration testing refers to methods that include excavating a significant portion of the proposed infiltration area, filling the excavation with water, and monitoring drawdown. The excavation should be to the depth of the proposed infiltration surface and ideally be at least 30 to 100 square feet.

D.5.3 Design Related Considerations for Selection of an Infiltration Factor of Safety

Design related considerations include:

- Level of pretreatment and expected influent sediment loads – credit should be given for good pretreatment to account for the reduced probability of clogging from high sediment loading. Appendix B.6 describes performance criteria for "flow-thru treatment" based 80 percent capture of total suspended solids, which provides excellent levels of pretreatment. Additionally, the Washington State Technology Acceptance Protocol-Ecology provides a certification for "pre-treatment" based on 50 percent removal of TSS, which provides moderate levels of treatment. Current approved technologies are listed at: http://www.ecy.wa.gov/programs/wq/storm water/newtech/technologies.html. Use of certified technologies can allow a lower factor of safety. Also, facilities designed to capture runoff from relatively clean surfaces such as rooftops are likely to see low sediment loads and therefore may be designed with lower safety factors. Finally, the amount of landscaped area and its vegetation coverage characteristics should be considered. For example in arid areas with more soils exposed, open areas draining to infiltration systems may contribute excessive sediments.

- Compaction during construction – proper construction oversight is needed during construction to ensure that the bottoms of infiltration facility are not impacted by significant incidental compaction. Facilities that use proper construction practices and oversight need less restrictive safety factors.

Table D.5-2: Design Related Considerations for Infiltration Facility Safety Factors

Consideration	High Concern – 3 points	Medium Concern – 2 points	Low Concern – 1 point
Level of pretreatment/ expected influent sediment loads	Limited pretreatment using gross solids removal devices only, such as hydrodynamic separators, racks and screens AND tributary area includes landscaped areas, steep slopes, high traffic areas, road sanding, or any other areas expected to produce high sediment, trash, or debris loads.	Good pretreatment with BMPs that mitigate coarse sediments such as vegetated swales AND influent sediment loads from the tributary area are expected to be moderate (e.g., low traffic, mild slopes, stabilized pervious areas, etc.). Performance of pretreatment consistent with "pretreatment BMP performance criteria" (50% TSS removal) in Appendix B.6	Excellent pretreatment with BMPs that mitigate fine sediments such as bioretention or media filtration OR sedimentation or facility only treats runoff from relatively clean surfaces, such as rooftops/non-sanded road surfaces. Performance of pretreatment consistent with "flow-thru treatment control BMP performance criteria" (i.e., 80% TSS removal) in Appendix B.6
Redundancy/ resiliency	No "backup" system is provided; the system design does not allow infiltration rates to be restored relatively easily with maintenance	The system has a backup pathway for treated water to discharge if clogging occurs <u>or</u> infiltration rates can be restored via maintenance.	The system has a backup pathway for treated water to discharge if clogging occurs <u>and</u> infiltration rates can be relatively easily restored via maintenance.
Compaction during construction	Construction of facility on a compacted site or increased probability of unintended/ indirect compaction.	Medium probability of unintended/ indirect compaction.	Equipment traffic is effectively restricted from infiltration areas during construction and there is low probability of unintended/ indirect compaction.

D.5.4 Implications of a Factor of Safety in BMP Feasibility and Design

The above method will provide safety factors in the range of 2 to 9. From a simplified practical perspective, this means that the size of the facility will need to increase in area from 2 to 9 times relative to that which might be used without a safety factor. Clearly, numbers toward the upper end of this range will make all but the best locations prohibitive in land area and cost.

In order to make BMPs more feasible and cost effective, steps should be taken to plan and execute the implementation of infiltration BMPs in a way that will reduce the safety factors needed for those projects. A commitment to effective site design and source control thorough site investigation, use of effective pretreatment controls, good construction practices, and restoration of the infiltration rates of soils that are damaged by prior compaction should lower the safety factor that should be applied, to help improve the long term reliability of the system and reduce BMP construction cost. While these practices decrease the recommended safety factor, they do not totally mitigate the need to apply a factor of safety. The minimum recommended safety factor of 2.0 is intended to account for the remaining uncertainty and long-term deterioration that cannot be technically mitigated.

Because there is potential for an applicant to "exaggerate" factor of safety to artificially prove infeasibility, an upper cap on the factor of safety is proposed for feasibility screening. A maximum factor of safety of 2.0 is recommended for infiltration <u>feasibility screening</u> such that an artificially high factor of safety cannot be used to inappropriately rule out infiltration, unless justified. If the site passes the feasibility analysis at a factor of safety of 2.0, then infiltration must investigated, but a higher factor of safety may be selected at the discretion of the design engineer.

Appendix D: Approved Infiltration Rate Assessment Methods

Worksheet D.5-1: Factor of Safety and Design Infiltration Rate Worksheet

Factor of Safety and Design Infiltration Rate Worksheet			Worksheet D.5-1		
Factor Category		Factor Description	Assigned Weight (w)	Factor Value (v)	Product (p) $p = w \times v$
A	Suitability Assessment	Soil assessment methods	0.25		
		Predominant soil texture	0.25		
		Site soil variability	0.25		
		Depth to groundwater / impervious layer	0.25		
		Suitability Assessment Safety Factor, $S_A = \Sigma p$			
B	Design	Level of pretreatment/ expected sediment loads	0.5		
		Redundancy/resiliency	0.25		
		Compaction during construction	0.25		
		Design Safety Factor, $S_B = \Sigma p$			
Combined Safety Factor, $S_{total} = S_A \times S_B$					
Observed Infiltration Rate, inch/hr, $K_{observed}$ (corrected for test-specific bias)					
Design Infiltration Rate, in/hr, $K_{design} = K_{observed} / S_{total}$					
Supporting Data					
Briefly describe infiltration test and provide reference to test forms:					

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