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Modeling Water Quality Impacts of Stormwater Runoff – Why Hydrologic Models Aren't Sufficient

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It is a common practice in assessing water quality impacts of stormwater runoff to use hydrology-based "water quality" models to estimate total concentrations of chemical contaminants at a particular location in the runoff and receiving waters. Those estimates are then compared with U.S. Environmental Protection Agency (EPA) worst-case-based water quality criteria and state water quality standards to render judgments about water quality impacts. However, the results of stormwater hydrology-runoff models do not, in fact, properly assess water quality impacts.

Chemical composition versus water quality

A fundamental error made in the water quality management field is the consideration of chemical concentrations (as typically measured by EPA or "Standard Methods" analytical procedures) as being synonymous with water quality. By Clean Water Act requirements, water quality is assessed relative to the designated beneficial uses of a water body. Since it is not possible to directly translate total concentration of a chemical in either a discharge or within a water body to an impairment of beneficial uses, it is not appropriate to characterize a set of chemical concentration data as an assessment of water quality. While such data describe certain water characteristics, it is only when those characteristics are appropriately integrated with other information, such as chemical bioavailability and behavior, duration of organism exposure, organisms of interest, habitat characteristics, desired use of the water body, et cetera, that they can provide insight into the role of those chemical contaminants in water quality—their impact on beneficial uses of the waterbody.

Additionally, chemical *constituent* or *contaminant* is not synonymous with chemical *pollutant*. Chemical contaminants or constituents are only pollutants when they adversely impact the beneficial use of a particular water body (for example, cause toxicity that affects organisms of concern, cause bioaccumulation of chemicals in edible organisms to render them unsuitable for use as food, change organism assemblages, adversely affect the character of the water for domestic water supply, et cetera, depending on the water body). This nomenclature distinction recognizes the paramount role of site-specific aquatic chemistry and toxicology/biology in water quality evaluation and more properly focuses the public and private funds available on cost-effective water quality protection and management. Focusing on chemical impacts rather than on concentrations of regulated chemicals also enables better focus on assessment of the impact of unregulated constituents—those without numeric water quality criteria/standards—that may be causing water quality impairment.

The current approach of finding an exceedance of a numeric water quality criterion/standard and then developing treatment works/control programs, without properly evaluating whether or not the exceedance is, in fact, adversely affecting beneficial uses of the water body, can waste public and private funds and at the same time fail to address significant water quality problems in the water body. This is especially true in the evaluation and management of water quality problems associated with stormwater runoff from urban and rural/agricultural areas, and in water quality modeling.

Aquatic chemistry

There is a general lack of consideration of the importance of aquatic chemistry in water quality evaluation and management. Aquatic chemistry can be complex and not easily modeled; its proper incorporation requires a more in-depth understanding than many in the field possess. It can also be more challenging to explain why removal of particular "chemicals" in a situation is not warranted for water quality protection than it is to cause the development of a treatment works. That notwithstanding, it has been well-known since the late 1960s that the total concentrations of potentially toxic constituents in the water column or sediment is an unreliable basis for estimating the water quality impacts on the Clean Water Act-designated beneficial uses of a water body.

The reason that total concentrations of a selected chemical(s) are unreliable in assessing water quality/use-impairment is that many chemical constituents in aquatic systems exist in a variety of chemical forms, only some of which are toxic or otherwise available to affect water quality adversely. This is shown conceptually in the aquatic chemistry "wheel" presented in Figure 1.

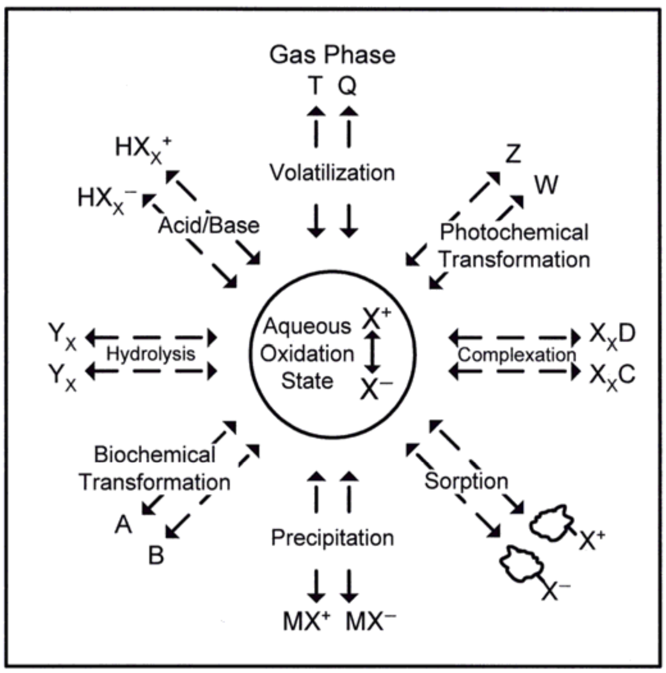

Figure 1: Aquatic chemistry of chemical constituents

Different forms of a chemical can have vastly different degrees of impact on the beneficial uses of a water body (such as aquatic life propagation or wholesomeness of aquatic life used as food). The forms in which chemicals exist in a particular aquatic system depend on the nature and levels of detoxification materials in the water and sediments. Those materials, such as organic carbon, sulfides, carbonates, hydrous oxides, clay minerals, et cetera, react with potentially toxic forms of chemicals, yielding chemical forms that are non-toxic, less toxic, or otherwise less available to aquatic life. The reactions that take place and the toxicity/availability of the various forms of chemicals that are created through these reactions depend on the nature of the particular contaminant, as well as the characteristics of the aqueous environment being considered.

In an attempt to better represent aquatic chemistry in water quality assessment, the EPA developed the MINTEQA2 exposure assessment model. (Information on that model and its use is available at https://www.epa.gov/exposure-assessment-models/minteqa2.) MINTEQA2 can be used to some extent to describe the position of equilibrium for the potential reactions that a chemical may undergo in an aqueous environmental system. However, it does not account for the kinetics of those reactions—the rates at which equilibrium is attained—and hence the actual concentrations of the various forms expected in a particular system. Thus, while the MINTEQA2 model is useful in describing the aquatic chemistry of a constituent, it must be used in conjunction with site-specific investigations of the location to which it is being applied. The purpose of those site-specific investigations is not the quantitative speciation of a chemical, but rather evaluation of the availability of the forms that are present through effects-based assessments.

Duration of exposure

In addition to considering the bioavailability of the chemical species present in a given aquatic system, it is necessary to consider the duration of exposure that aquatic life of concern can receive as the runoff waters mix into the receiving waters. Figure 2 illustrates the general relationship among the concentration of available chemical forms, duration of organism exposure, and laboratory toxicity measurement (impact).

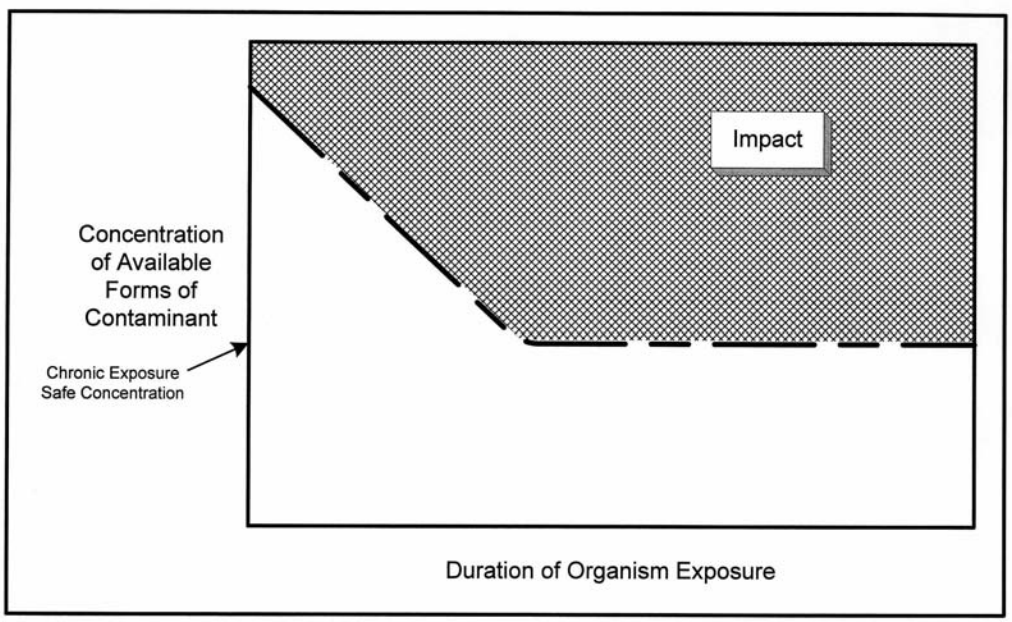

Figure 2: Critical concentration/duration of exposure relationship

As shown, comparatively high concentrations of available forms of a toxic chemical can be tolerated by aquatic organisms without impact as long as the duration of exposure is sufficiently short. As the duration of exposure is increased, the concentration of available forms that can be tolerated without impact lessens until, for many chemicals, a concentration is reached to which an organism can be exposed for a lifetime or over critical life stages without adverse impact. How this relationship is manifested in an aquatic environment can be influenced by the characteristics of the organisms of concern, the nature of the discharge being considered, as well as the hydrodynamics of the receiving water.

Some discharges, such as stormwater runoff, are short-term and episodic in nature; organisms would be unlikely to be exposed to the discharge for a substantial duration. Mobile organisms such as fish may move in and out of an effluent/receiving water mixing area, altering the exposure it receives to contaminants in the discharge. There can be characteristics of a discharge, such as its temperature, that attract fish to it; other characteristics may repel fish. Some discharges contain some aspects that attract fish as well as others that repel them. These discharge characteristics, thus, affect the exposure a mobile organism may receive. There may also be zones of passage in a receiving water such that a mobile organism may avoid exposure altogether. To reliably model potential water quality impacts of stormwater runoff it is necessary to conduct site-specific studies of the mixing of the runoff waters with the receiving waters.

Since the concentrations of potential pollutants in runoff are typically the greatest at the point at which the runoff enters the receiving water, there is concern about whether there can be toxicity to aquatic life at or near the point of runoff entry. There is also concern about toxicity in areas outside of the mixing zone of runoff with the receiving water. The concentrations of runoff-associated contaminants in those areas are typically substantially more dilute than those in the runoff water itself. Potential impacts within the mixing zone, as well as out of the mixing zone, need to be addressed. One of the difficulties with the application of some states' regulations to stormwater runoff is that they do not allow a mixing zone for runoff-associated constituents in the receiving waters. Such a regulatory approach presumes that the concentrations in the discharge persist in the receiving water, which is rarely the case.

Recommended approach

Evaluation of the impact of chemical contaminants in a discharge on water quality should begin with the reliable definition of the water quality/use-impairment that is of concern. The water pollution control programs need to be shifted from comparing concentrations of chemicals to worst-case-based standards/guidelines to reliably assessing impacts on beneficial uses of a water body. If the beneficial uses of a water are being adversely impacted, a toxicity identification evaluation (TIE) approach needs to be followed to determine the cause/source of the problem. This is in contrast to, for example, measuring copper, lead, zinc, and cadmium that typically occur in street and highway stormwater runoff, finding they exceed EPA worst-case-based numeric water quality criteria/state water quality standards, and declaring that an impact has occurred.

We described an Evaluation Monitoring approach (see discussion at http://www.gfredlee.com/Runoff/wqchar_man.pdf) to focus monitoring on chemical impacts rather than on chemical concentrations. If toxicity is found in laboratory tests of an effluent or receiving water, an assessment should be made as to whether such toxicity is manifested in the water of concern and whether that toxicity significantly adversely affects the water body's beneficial uses. It should not be assumed that toxicity measured in a standard laboratory toxicity test necessarily translates to toxicity that is significantly altering the numbers, types, or characteristics of desirable forms of aquatic life in a water body. This is especially true for situations such as urban-area and highway stormwater runoff, where there can be short-term pulses of contaminants associated with runoff events that are not of sufficient magnitude and duration to exceed the critical magnitude—duration of exposure needed to be adverse to important forms of aquatic life in a water body.

For example, in the mid-1990s, G. Fred Lee, Ph.D., P.E., DEE, and Scott Taylor, P.E., initiated Evaluation Monitoring studies on the toxicity and water quality impacts of heavy metals in urban-area street and highway stormwater runoff in the Upper Newport Bay watershed in Orange County, Calif. It had previously been found, as is typical in urban-area and highway runoff, that several heavy metals, including copper, lead, and zinc, were present in runoff from those areas in concentrations above EPA worst-case-based water quality criteria. That finding indicated that there was a potential for those heavy metals to cause aquatic life toxicity in the waters receiving the runoff.

In the Evaluation Monitoring studies conducted, samples of stormwater runoff were collected from 10 watersheds covering urban, highway, and agricultural areas. The studies showed that stormwater runoff from urban areas and highways frequently contained heavy metals in concentrations above EPA water quality criteria. They also showed that that runoff was toxic to the zooplankton, Ceriodaphnia, with as much as 10 TUa of acute aquatic life toxicity. TIEs involving the addition of ethylene diamine tetra acetic acid (EDTA) to the toxicity tests to complex (render non-toxic) copper and other heavy metals, however, revealed that the toxicity was not due to heavy metals. Rather, it was found that the toxicity was due to organophosphate-based pesticides, including diazinon and chlorpyrifos, and likely as well to pyrethroid-based pesticides used in the watersheds studied.

The Lee and Taylor studies demonstrated the appropriateness of using the Evaluation Monitoring approach to evaluate the potential water quality impacts of stormwater runoff-associated potential pollutants. The overall report covering those studies is available for download at http://www.gfredlee.com/Watersheds/Heavy-metals-319h.pdf and
http://www.gfredlee.com/Watersheds/295-319-tox-paper.pdf

Conclusion

To reliably model the water quality/beneficial-use impacts of a chemical constituent in stormwater runoff or wastewater discharges, detailed information on aquatic chemistry, thermodynamics and kinetics, and mixing and transport/mixing processes that occur on a site-specific basis, as well as the water quality significance of the forms of contaminants, need to be properly incorporated into the modeling effort. It is rare that this type of information is available or can be developed without extensive, site-specific investigations. It is far more reliable to follow the Evaluation Monitoring approach to evaluate the water quality impacts of pollutants in runoff/discharges. This includes directed, site-specific investigation and evaluation of the water quality impairments such as aquatic life toxicity, excessive bioaccumulation of hazardous chemicals, et cetera. Where impairment is found, follow-on studies are needed to determine the cause of the impairment and the sources of constituents causing the impairment, and to develop control programs to eliminate the impairment of the water quality/beneficial uses of the water body of concern.

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This article is condensed from a report by G. Fred Lee & Associates: “Modeling Water Quality Impacts of Stormwater Runoff-Associated Pollutants,” September 2007. The report is available online at www.gfredlee.com/Runoff/StormwaterWQModeling.pdf .