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NATIONAL IRRIGATION WATER QUALITY PROGRAM
INFORMATION REPORT NO. 3

Guidelines for Interpretation of the Biological Effects of Selected Constituents in Biota, Water, and Sediment

Introduction

Participating Agencies:

Bureau of Reclamation
U.S. Fish and Wildlife Service
U.S. Geological Survey
Bureau of Indian Affairs

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Introduction

The guidelines, criteria, and other information in this volume were originally compiled for use by personnel conducting studies for the Department of the Interior's National Irrigation Water Quality Program (NIWQP). The purpose of these studies is to identify and address irrigation-induced water quality and contamination problems associated with any of the Department's water projects in the Western States. When NIWQP scientists submit samples of water, soil, sediment, eggs, or animal tissue for chemical analysis, they face a challenge in determining the sig-nificance of the analytical results. How much of a given chemical constituent is "normal" in the tested medium? How much is unusually high? What adverse effects— if any— may result from the reported concentration? Studies that address these questions are myriad: they are widely scattered in the literature, they use many different approaches and testing protocols, and they yield greatly varying— and sometimes contradictory— results. The chapters in this volume are intended to: (1) identify the most important, most relevant studies for several "constituents of concern" that are commonly encountered in environments affected by irrigation drainage; (2) present a sampling of notable results from these studies in tables organized according to tested medium; (3) explain further, in the accompanying text, the significance of these results; and (4) give full and accurate references to the original studies, for those who desire more detailed information.

Although this volume is targeted for scientific specialists, it may also be of interest to government officials, farmers, ranchers, conservationists, reporters, and anyone else interested in the environmental health of freshwater ecosystems. These readers may find the glossary in Appendix II especially helpful.

The Limitations of This Volume

It is important to note five limitations on the material presented here:

(1) Out of the hundreds of substances known to affect wetlands and water bodies, this volume focuses on only nine constituents or properties commonly identified during NIWQP studies in the Western United States— salinity, DDT, and the trace elements arsenic, boron, copper, mercury, molybdenum, selenium, and zinc. Financial and time restraints do not allow consideration of other contaminants at this time.

(2) For the most part, these are only guide-lines, merely reports of toxic effects that were noted for certain concentrations in particular circumstances. Individual constituents may be more or less toxic at other sites or for other species, depending on many factors. Some of these com-plicating factors are described in the following section on data interpretation, which readers are urged to review before attempting to apply these guidelines.

(3) Caution is particularly appropriate in using the summary tables (the first numbered table in each of the chapters). These are designed to give only a general indication of concentrations that may be troublesome in various types of media. In some cases the "no effect" and "threshold" values for a class of organisms have been distilled from hundreds of individual studies of the diverse species that make up the class. In other cases, we have had to rely on only a handful of studies to set *tentative* values for the entire class. Readers should make no final, formal decisions regarding the toxicity of

a particular compound to a particular species without consulting the more detailed information presented later in each chapter and, when possible, the original studies.

(4) Results from many recent studies could not be included here. Most of the research for these chapters was completed by mid-1996, and only the literature pub-lished prior to that time was system-atically surveyed. During subsequent review and preparation of this volume, more recent results that came to our attention were added opportunistically, not systematically.

(5) Legally enforceable standards are not presented here, with two exceptions. The U.S. Environmental Protection Agency has established "maximum contaminant levels," applicable only to drinking water, for most of these constituents, and the U.S. Food and Drug Administration has "action levels for human consumption" for two of them (DDT and mercury). These legal standards are noted near the end of each chapter, in the section "Regulatory standards." Note, however, that even in those sections, values identified as "goals" or "criteria" do not have the force of law.

Individual States may set legal standards that are stricter than those of the Federal Government, and many have chosen to do so. State standards are too variable and voluminous to be listed here; however, Appendix I lists addresses and phone numbers for the offices responsible for water quality standards in each of the 17 Western States.

The Need for Caution in Interpreting Toxicological Data

The contents of this report are described as *guide lines*, rather than rules or standards, because toxicological effects vary greatly in natural ecosystems. Many variables can cause individual constituents to be more or less toxic at other sites or for other species. This section describes some of the better known factors that may complicate the interpretation of toxicity data.

Unnatural Laboratory Settings

Most laboratory studies test toxicity under completely unnatural conditions: they test the effect of a single compound on a single species, delivered by only one pathway under carefully controlled conditions. In the wild, organisms are exposed to many different chemical and physical agents simultaneously. (See "Interactions," below.)

Generally, laboratory specimens in an experimentally contaminated environment are given food from outside, uncontaminated sources, whereas wild creatures must eat food that has grown in the same environment and that may have accumulated, through bioconcentration, lethal levels of whatever toxins are present. Thus, for instance, fish or waterfowl could end up dying in areas where waterborne toxin concentrations are at levels that caused no harm to laboratory specimens.

On the other hand, most laboratory specimens are taken from uncontaminated populations, which have no previous history of exposure to the toxin being tested. In the wild, organisms living in a contaminated environment may have acclimated or adapted to the toxin, especially if the contamination developed gradually. In this case, one might find fish and waterfowl thriving in areas where waterborne concentrations are at levels experimentally determined to be lethal.

Laboratory specimens are rarely threatened by predators or challenged by others of their own kind in mating competitions, whereas their undomesticated cousins deal with both conflicts. These conflicts can add to the overall stress on the organisms, making them more susceptible to toxic effects. Conversely, the higher metabolic

rates of creatures in conflict may help them dispose of toxins more readily.

These differences between natural and laboratory environments mean that measure-ments collected in natural settings are generally preferable to laboratory measure-ments for predicting toxic effects in natural systems. In cases where natural studies are lacking, though, the laboratory studies may provide the only useful guidance to possible toxic effects. Moreover, only in controlled laboratory studies can the effects of individual variables be studied, by holding all other factors constant.

Interactions

The toxicity of an element or compound may be either reinforced or weakened through its interaction with other substances. In toxi-cology studies, such interactions are generally classified as being adversely additive, syner-gistic (greater than additive), or antagonistic (less than additive or even acting as antidotes to one another). For instance, various chapters in this volume describe synergistic relationships between boron and selenium, between copper and zinc, and between DDE and Arochlor, meaning that when both agents are present, their toxic effect is greater than would be expected just from adding together their individual effects. Elsewhere, these chapters describe antagonistic relationships between arsenic and selenium and between cadmium and copper: tests show these combinations of elements to be *less* toxic than either one would be by itself. In the case of selenium and mercury, however, the selenium chapter cites a study (Heinz and Hoffman 1996) showing that these two elements are antagonistic to each other in their effect on adult mallards but synergistic in their effect on mallard reproduction.

In some cases, two substances that interact antagonistically at first may eventually become synergistic with increasing concentrations. For instance, some interactions may transform a toxic compound to a less toxic, but also less soluble, form. These low-solubility compounds may then accumulate in the liver, the kidneys, or other bodily organs, eventually overtaxing the capacity of these storage sites. Physical damage may occur to organs storing too many solids.

However, our understanding of biogeo-chemical interactions is still rudimentary. The potential combinations of trace elements are essentially infinite, and research thus far has defined the additive, antagonistic, and synergistic effects of only a few simple com-binations. Some compounds cause toxic effects by interfering in essential chemical metabolic pathways, yet different chemical species of the same two elements may interact on different metabolic pathways and produce a completely different result. Under present conditions it takes years of research— perhaps an entire career— to positively define just one or two complex metabolic chemical pathways. Many apparent discrepancies appear in the literature.

Temperature

All organisms have optimal temperature ranges in which they function most efficiently. Outside of these ranges they will be more susceptible to toxins. The DDT chapter, for instance, cites studies showing that both high and low temperatures increase the toxicity of DDT to the water flea *Daphnia*. Temperature fluctuations affect the rate of chemical reactions, the solubility of chemical species, and the metabolic rates of organisms. High temperatures generally increase the chemical reaction rate and the solubility of most solid substances. Oxygen and other gases, however, are more soluble in cold water than in warm. The effect of temperature on metabolism depends on whether organisms are exothermic

("cold blooded") or endo-thermic ("warm blooded"). Among exo-therms, such as fish and invertebrates, higher temperatures cause metabolic rates to rise. Endotherms, such as birds and mammals, increase their metabolic rate at lower temper-atures in order to maintain a constant body temperature. An elevated metabolism increases the intake of a toxin and distributes it more rapidly to sensitive organs within the body.

Water Chemistry

The effect of any toxin may be altered by variations in water hardness, pH (acidity/ alkalinity), and dissolved oxygen content. Water hardness, for instance, causes such great variation in the toxicity of copper and zinc that the Environmental Protection Agency, rather than setting fixed values as the freshwater criteria for these elements, has instead established formulas that make the criteria relative to hardness. (See tables at end of copper and zinc chapters.)

Disease

It seems likely that populations weakened by disease would be more susceptible to toxins and vice versa. According to Sprague (1985), though, the empirical evidence for this relationship is scanty. At the very least, the presence of disease in a population can complicate the task of interpreting which deaths and other adverse effects are attributable to toxins and which are due to the disease.

Nutrition

A species' susceptibility to toxins may be affected not only by a shortage of food but also by variations in the quality of the food. Organisms obliged to deviate from their customary diets may lack crucial vitamins, minerals, or proteins that play a role in detoxifying harmful compounds.

Sampling Biases

Interpretation of field data for plants and animals can be confounded by a sampling bias that favors "survivors." Most biological sampling techniques are designed to sample live biota. In contaminated environments, live biota represent "survivors" and, hence, these are likely to be the organisms that either were less sensitive to the toxin or had less exposure to it. Bird eggs are probably less affected by this bias than other media because they are sampled without regard for the status of the embryo inside the egg. So long as the egg is intact, live and dead embryos have equal probabilities of being sampled.

Off-Site Exposure

Some organisms travel considerable distances and may be exposed to toxins at places other than the site where they are collected. Many birds, for example, may feed several kilo-meters away from their nesting sites. Hence, responses such as teratogenesis among their offspring may not be attributable to contami-nation in the immediate vicinity. Although this complication is obviously most pro-nounced in the case of birds, many mammals, fish, and even insects also travel widely.

Confusion About Measurements

Chemical concentrations in plants, animals, soil, sediment, and water are measured in various ways, and there is even greater variety in the ways these measurements are expressed. Although all contributors to this volume have endeavored to clarify both the type of measurement and the units of measure for every value presented, some may remain unclear. Concentrations in any solid medium (such as

organic tissues, sediment, or animal feed) may be measured on either a dry-weight (dw) basis or a wet-weight (ww) basis. The resulting values are markedly different, and the dw value is invariably higher. In fish and animal tissues, the dw concentration is generally in the range of 3 to 5 times the ww value, but there is no set conversion factor. The ratio between dw and ww depends on the water content of the tissue, which varies between species and between organs, and even varies within individual organs over time. Criteria based on wet-weight measurements should not be used to assess the toxicity of dry-weight concentrations, and vice versa.

"Fresh weight" describes a wet-weight measurement that is made either in the field or within a few hours after collection. Media such as eggs and animal tissue may begin losing water as soon as they are collected, which results in higher wet-weight concentrations of most other constituents if they are not analyzed promptly.

Many chemical elements have two or three different valences or oxidation states that are common in the environment, and the toxicity of these varying forms can differ greatly. Arsenic (III), for instance, is much more toxic than arsenic (V), yet some tests do not differentiate between these forms and report only "total arsenic." A criterion established using arsenic (III) would be misleadingly low in most natural settings, for arsenic (V) is usually more abundant.

Even where the valence state doesn't vary, the various compounds an element makes with other elements can greatly affect toxicity. Dimethyl mercury (C_2H_6Hg), for instance, is far more poisonous than mercuric sulfide (HgS), even though both of them are based on mercury (II). It is common for organic (carbon-based) compounds to be more toxic than others because they are more readily taken up in the metabolism of living organisms.

Concentrations of elements or compounds in water may be measured in two different ways. Under one method, water samples are filtered before analysis to remove all microorganisms and other suspended particles. The resulting measurement is called a *total dissolved* concentration. In the other method, no filtering is done, and the resulting measurement is a *total recoverable* concentration. The difference between these figures can be strongly influenced by the overall biotic productivity of a water body. In highly productive waters, both nutrients and toxins are quickly taken up by microorganisms, leaving only small amounts of these dissolved in the water column. Thus, a measurement showing only dissolved constituents may miss significant amounts of toxins that are nonetheless present in the water column and available through the food chain. Where productivity is low, the dissolved concentration will be very close to the total recoverable concentration.

Many reports give chemical concentrations in either parts per million (ppm) or parts per billion (ppb). A few use the ambiguous abbreviation "ppt," which may stand for either parts per thousand or parts per trillion. Obviously, in reading such reports, it is important to know which meaning of "ppt" was intended. In accordance with principals of the International System of Units, most concentrations in this volume are expressed in units of either weight per weight (for solid media) or weight per volume (for liquids). Here is a brief list of equivalents that clarify how these units relate to one another:

Parts per thousand (ppt *or* per mil *or* ‰)	=	g/kg *or* g/L
Parts per million (ppm)	=	mg/kg *or* mg/L
Parts per billion (ppb)	=	µg/kg *or* µg/L
Parts per trillion (ppt)	=	ng/kg *or* ng/L

The relationship shown here between weight/weight measurements and weight/volume measurements comes about because 1 liter of water weighs almost exactly 1 kilogram.

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