

Chemicals in California drinking water: source contaminants, risk assessment, risk management, and regulatory standards

Richard H.F. Lam^{a,*}, Joseph P. Brown^a, Anna M. Fan^a, Alexis Milca^b

^a *Office of Environmental Health Hazard Assessment, Pesticide and Environmental Toxicology Section, Berkeley, CA 94704, USA*

^b *Department of Health Services, Office of Drinking Water, Berkeley, CA 94704, USA*

Abstract

Monitoring studies from 1983 to 1992 of water supply and drinking water wells in the state for organic contaminants indicated that more than 80 chemicals were present in ground water. Most of the chemicals detected occurred infrequently and at levels below the current water quality criteria (maximum contaminant level, MCL, or action level, AL). Drinking water wells with levels exceeding these criteria were either closed or had remedial actions taken. Dibromochloropropane (DBCP), simazine, diuron, atrazine, tetrachloroethylene (PCE), and trichloroethylene (TCE) were some of the chemicals detected most frequently in these studies. DBCP, simazine, diuron, and atrazine are agricultural pesticides and are either no longer registered or restricted for use as active ingredients. Special chemical contaminants of concern in ground water are nitrate, arsenic, fluoride, and radon. Surface water from rain and snow runoffs from the Sierra Nevada provides drinking water for most of the San Francisco Bay Area. This water is considered pristine and requires only treatment against disease-causing microorganisms. Most of Southern California depends on surface water from the Sacramento–San Joaquin River Delta and the Colorado River. The quality of water in the Delta is affected by discharges of pollutants into the watersheds of the Sacramento and San Joaquin Rivers and the intrusion of seawater from the San Francisco Bay. The major concern of most water utilities with regard to the use of Delta water for drinking is the formation of trihalomethanes (THMs) and other disinfection by-products. California can promulgate its own regulations which are frequently more stringent than the federal regulations. Standards have also been established for many water contaminants that are uniquely found in California. This report presents the state and federal drinking water standards for 19 inorganic, 66 organic, and 10 other chemicals, mainly radionuclides.

1. Water sources

California relies on both ground and surface water for its source of drinking water. The quality of drinking water in the state depends on the source from which it is

* Corresponding author.

obtained. Most residents of the San Francisco Bay Area obtain their drinking water which originates as rain or snow in the Sierra Nevada. This water is brought to consumers by way of the Hetch Hetchy and Mokelumne Aqueducts, bypassing the Sacramento–San Joaquin River Delta. According to traditional criteria, this water is considered pristine, with the only treatment required being that against disease-causing organisms such as *Giardia lamblia*, *Cryptosporidium*, and coliform bacteria as required by the state surface water filtration and disinfection treatment rule. Southern California depends on surface waters from the Sacramento–San Joaquin River Delta and the Colorado River. The California State Water Project (SWP) pumps drinking water destined for Southern California from the South Delta into the California Aqueduct to four terminal reservoirs for delivery to southern water supply agencies. The quality of the water in the Delta, especially from its southern portion, is affected by discharges of pollutants in the watersheds of the Sacramento and San Joaquin Rivers and seawater intrusion from the San Francisco Bay. Many communities in the Central Valley and rural areas depend on ground water as their principal source of drinking water. Ground water basins cover much of the state and most are considered suitable, or potentially suitable, for municipal or domestic water supply. Ground water is vulnerable to contamination by pollutants that enter the ground and affect drinking water supplies. Currently, many basins are only partially assessed for ground water contamination, and some basins have never been monitored.

The blending of water from surface and ground water sources is common among water utilities. Drinking water quality problems in some parts of the state are further complicated by some water systems withdrawing water from sources originally planned for agricultural and industrial uses. Issues concerning the remediation of contaminated surface and ground water and the control of pollutant release into these water sources are beyond the scope of this review.

2. Regulation of ground and surface water

The responsibility of protecting ground and surface water in the state is divided among various local, state, and federal agencies. State agencies with major roles are the State Environmental Protection Agency (Cal/EPA), the State Health and Welfare Agency (CHWA) and the State Resources Agency (CRA). Departments within these agencies that play major roles are:

- The Department of Water Resources (CDWR), CRA, manages the water resources of the state. CDWR also monitors for water contamination under the Ground Water Level Monitoring Program, Toxic Chemicals in Ground Water Program, and Water Quality Evaluations Program.

- The State Water Resources Control Board (SWRCB), Cal/EPA, regulates the discharge of waste that may affect the quality of drinking water under the Porter–Cologne Water Quality Control Act of 1969. The SWRCB assists and oversees the nine Regional Water Quality Control Boards which formulate, adopt, and implement water quality control policies within their own jurisdictions.

– The California Department of Health Services (CDHS), CHWA, pursuant to Title 22 of the California Administrative Code, and the Safe Drinking Water Act of 1989, has the responsibility for oversight of public drinking water supplies via the promulgation, implementation, and enforcement of drinking water standards.

– The Office of Environmental Health Hazard Assessment (OEHHA), Cal/EPA, performs risk assessments of chemicals for evaluation of actual or potential contamination situation and establishes health-based permissible levels and health-based advisory levels for chemical pollutants in drinking water, which are protective of public health. OEHHA also administers the Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65).

Other departments that are involved in activities that relate to and which affect water quality are the Department of Toxic Substances Controls (DTSC) and the Department of Pesticide Regulation (CDPR) within Cal/EPA. DTSC controls a number of chemical-handling activities that affect surface and ground water quality under the California Hazardous Waste Control Act of 1972, the Federal Resources Conservation and Recovery Act of 1976 (RCRA), and the state and federal superfund cleanup programs. CDPR regulates and administers controls on pesticide applications, pursuant to the California Food and Agricultural Codes.

On the federal level, the US Environmental Protection Agency (US EPA) is the most active in drinking water protection. Besides overseeing state programs which have established primacy, it also coordinates with state agencies in implementing programs where primacy has not been granted. The US EPA also enforces many state programs, and provides grants to support research on ground and surface water. The US Geological Survey (USGS) provides hydrologic information and data needed for the management of water resources and, therefore, assists many agencies in their surface and ground water protection efforts.

3. Source contaminants

3.1. Ground water

Ground water provides about 39% of California's water requirements for municipal, industrial, and agricultural uses [1]. Contamination in ground water has occurred in various areas throughout the state. Areas identified are the coastal region extending from Orange County to Santa Clara County, and in the San Joaquin and Sacramento Valleys. Major sources of ground water pollution are agriculture, industry, dairy farms, mining, chemical leaks and spills, urban runoff, leaking underground storage tanks and septic systems (cesspools).

3.1.1. Organic contaminants

Ground water basins of the state were thought to be relatively safe from pollution by pesticides, until dibromochloropropane (DBCP) was found to contaminate hundreds of wells in the San Joaquin Valley in the 1970s. Since then, DBCP has been found in over 2000 wells (water supply and irrigation wells) statewide and more than

80 other organic contaminants (pesticides and industrial chemicals) have been found in the ground water of 44 counties [2-4]. In a report to the Legislature in 1992, it was reported that of the 35 pesticides found in ground water, only 12 were the result of routine agricultural use [5]. These were aldicarb sulfone and aldicarb sulfoxide (metabolites), atrazine, bentazon, bromacil, 1,2-dichloropropane, DBCP, diuron, ethylene dibromide, prometon, simazine, and 2,3,5,6-tetrachloroterephthalic acid (TPA), a breakdown product of chlorthal-dimethyl. Among these pesticides, DBCP, 1,2-dichloropropane, and ethylene dibromide are no longer registered for use in California. DBCP was detected most frequently in ground water, followed by simazine, diuron, and atrazine (Table 1).

A worrisome recent development is the detection of new organic contaminants (14 new compounds since 1991) and detections in new counties (24 counties). First-time detections include dicamba, 2-(2,4-dichlorophenoxy)propionic acid (2,4-DP), ethylene dichloride, heptachlor, heptachlor epoxide, methoxychlor, methyl trithion, naphthalene, prometryn, propazine, 1,1,2,2-tetrachloroethane, tetrachloroethylene, thiobencarb and 1,2,4-trichlorobenzene. These chemicals occurred infrequently and only ethylene dichloride, naphthalene and 1,1,2,2-tetrachloroethane were found at levels above the water quality criteria [maximum contaminant level (MCL) or US EPA, Lifetime Health Advisory (US EPA, HAL)]. However, three chemicals (2,4-DP, methyl trithion, and prometryn) do not as yet have any health standards (or criteria) established.

Table 1

Most frequently detected pesticides in water supply wells under CDPR Well Inventory Data Base (1983-1992)^a

| Chemical | Total no. of contaminated wells | Maximum concentrations detected ($\mu\text{g/l}$) | Water quality criteria ($\mu\text{g/l}$) |
|---|---------------------------------|---|--|
| DBCP | 2721 | 8000 | 0.2 ^c |
| Simazine | 441 | 49.2 | 4 ^c |
| Diuron | 207 | 4.0 | 10 ^d |
| Atrazine | 181 | 8.5 | 3.0 ^c |
| 1,2-Dichloropropane | 136 | 160.0 | 5.0 ^c |
| Bromacil | 116 | 20.0 | 90 ^d |
| EDB | 115 | 4.7 | 0.02 ^c |
| Bentazone | 77 | 20 | 18 ^c |
| Aldicarb | 33 | 49.0 | 3.0 ^c |
| Aldicarb sulfone | 44 | 1281 | 2.0 ^c |
| Aldicarb sulfoxide | 19 | 13.2 | 4.0 ^c |
| TPA (2,3,5,6,-tetrachloro terephthalic acid) ^b | 31 | 15.0 | 4000 ^d |
| Prometon | 34 | 80.0 | 100 ^d |

^a Source: CDPR (1992).

^b TPA is a breakdown product of the active ingredient chlorthal-dimethyl.

^c MCL.

^d US EPA, HAL.

In the CDPR data base, the sampled water supply wells are not differentiated as to whether they are used as a source of drinking water or for irrigation. Many water supply wells, especially in rural areas, are known to have dual purposes. Public drinking water wells throughout California were sampled by the CDHS since 1984–1990, as mandated by AB 1803 (Chapter 881, Statutes of 1983), to determine how many wells have been contaminated by organic pollutants. Monitoring was first conducted on large supply systems (more than 200 connections) and later on small systems (5–199 connections) [6, 7]. Between 1984 and 1990, 7712 wells were sampled and 921 of them were found to be polluted with one or more chemicals. Of these, 321 of the drinking water wells were found to exceed one or more state drinking water standards. Table 2 shows the organic chemicals most frequently detected in the monitoring of drinking water wells under AB 1803 (combined large and small public water systems). DBCP is the most frequent organic chemical found, followed closely by tetrachloroethylene (PCE) and trichloroethylene (TCE). Chloroform, bromodichloromethane, and chlorodibromomethane, found in many wells, are probably formed in the chlorination of well water. Wells with concentrations of organics above the MCL or action level (AL) were either closed or had remedial action taken to reduce the level below the drinking water standards. In all cases, water delivered to

Table 2

Most frequently detected organic contaminants in drinking water wells sampled under AB 1803^a

| Chemical | Total no. of contaminated wells | Maximum concentration detected ($\mu\text{g/l}$) | Maximum contamination level ($\mu\text{g/l}$) |
|-----------------------------------|---------------------------------|--|---|
| Dibromochloropropane | 275 | 7.4 | 0.2 |
| Tetrachloroethylene | 264 | 166 | 5 |
| Trichloroethylene | 217 | 538 | 5 |
| Chloroform | 169 | 120 | 100 ^c |
| 1,1,1-Trichloroethane | 99 | 202 | 200 |
| 1,1-Dichloroethylene | 72 | 78 | 5 |
| Carbon tetrachloride | 45 | 29 | 0.5 |
| Bromodichloromethane | 43 | 40 | 100 ^c |
| Atrazine | 42 | 2.4 | 3 |
| Dibromochloromethane | 39 | 30 | 100 ^c |
| 1,2-Dichloroethane | 36 | 24 | 0.5 |
| 1,2-Dichloroethylene ^b | 36 | 100 | 6 (cis) 10 (trans) |
| Simazine | 32 | 28 | 4 |
| Bromoform | 27 | 78 | 100 ^c |
| 1,1-Dichloroethane | 28 | 30 | 5 |
| 1,2-Dichloropropane | 26 | 53 | 5 |
| Trichlorofluoromethane | 20 | 24 | 150 |

^a Source: CDHS (1986, 1990).

^b Combine cis and trans 1,2-DCE.

^c Combine trihalomethane (chloroform, bromodichloromethane, chlorodibromomethane, and bromoform).

consumers meets drinking water standards, although this is obtained in some instances by the blending of water from slightly contaminated wells with water from cleaner sources [8].

3.1.2. Inorganic contaminants

(i) Nitrate

Nitrate is a common ground water contaminant found in many agricultural areas in California. Nitrate in ground water occurs as a result of contamination by nitrogenous fertilizers, or by organic wastes from humans or animals. The principal health concern for excessive nitrate levels in drinking water is the development of methemoglobinemia in infants. After ingestion, nitrate is converted to nitrite in the gut of the infant. The absorbed nitrite reacts with hemoglobin in the blood, forming methemoglobin which significantly reduces the oxygen-carrying capacity of the blood. This gives rise to the 'blue baby' syndrome. More detailed environmental and toxicological assessment of nitrate can be obtained from other publications [9, 10].

According to the CDHS, more public water supply wells in California have been closed due to violations of the nitrate standard than of any other contaminant or class of contaminants [11]. Monitoring of water supply wells (drinking and irrigation wells) and public drinking water wells for nitrate showed that about 10% were found to have levels exceeding the drinking water standard of 10 mg/l of nitrate (measured as nitrogen, $\text{NO}_3\text{-N}$). Contaminated wells are found in the coastal counties of Orange, Los Angeles, San Diego, Ventura, Monterey, Santa Clara and Contra Costa and the agricultural zone of the Central Valley stretching from Kern County to Sacramento County.

(ii) Arsenic

Arsenic is found naturally in the environment in both organic and inorganic forms. Arsenate [As (V)] and arsenite [As (III)], the two inorganic forms of arsenic, which are much more toxic than the organic forms, are the forms commonly found in drinking water.

Since 1985, new human epidemiologic studies on arsenic have provided persuasive evidence that arsenic in drinking water not only causes skin cancer but can also cause liver and lung cancer and increases the risk of bladder, kidney, and nasal cavity cancers in both sexes, and prostate cancer in males [12–14]. Smith et al. [14, 15], in a recent analysis of the human data, estimated the cancer potency of arsenic, based on skin cancer, to be $5.3 \times 10^{-3}/\mu\text{g}/\text{kg d}$. With a 10^{-6} lifetime risk this is equivalent to a drinking water consumption of 2 l/d at a 6.2 ppt (0.0062 ppb) level. Comparable risks were estimated for other tumor sites, ranging from 0.2/1000 (liver cancer in males) to 17.2/1000 (lung cancer in females) at 2 l/d water intake at the present MCL of 50 $\mu\text{g}/\text{l}$ (ppb). The sum of all internal tumor sites at this exposure level gives a risk of 9.4/1000 and 17.3/1000 for males and females, respectively, and an average risk of 13.4/1000 [14, 15].

At 50 ppb the lifetime cancer risk of arsenic exposure via drinking water is approximately 1%, a risk comparable to radon exposure or second-hand cigarette smoke. Most public water systems have less than 25 ppb of arsenic in their drinking

water, and only 15 water systems in six counties have arsenic concentrations above the 50 ppb MCL. Some of these water systems have been able to meet the arsenic water standard by closing highly contaminated wells and blending water from others. In some areas, high arsenic levels in ground water can be a problem. In one area around North Edwards in the Mojave Desert, several drinking water wells have been found to have arsenic levels between 65 and 200 ppb, with one at 406 ppb. In the city of Hanford, about 35 000 residents are potentially exposed to arsenic above 50 ppb in their municipal water supply. The city will need to install treatment facilities to meet existing and future standards. On the basis of reevaluation of arsenic using newly available data on internal cancers, a lowering of the MCL is being considered by the US EPA possibly to the 5 ppb limit of detection [16]. At the analytical limit of detection of 5 ppb, more than 300 large water systems in the state may be out of compliance [17].

(iii) Fluoride

Fluoride, in the form of sodium fluoride, sodium silicofluoride, hydrofluorosilicic acid, or ammonium silicofluoride, is added to the drinking water of many utilities for the reduction of cavities in children. California's drinking water regulations specify that the average concentration of fluoride during any month if added to the water supply shall not exceed the MCL, of 1.4–2.4 mg/l, depending upon the annual average of daily maximum air temperatures.

The principal concern for excessive fluoride levels in drinking water is the development of dental fluorosis, which is characterized by mottled enamel of the teeth when exposure occurs during enamel formation, and osteofluorosis, commonly known as skeletal fluorosis. Skeletal fluorosis due to chronic exposure to high levels of fluoride can cause crippling, and maybe related to hip fractures in older people. It is considered by the US EPA as an adverse health effect. US EPA has maintained that dental mottling is a cosmetic defect and did not consider it in the setting of the fluoride MCL. Since dental fluorosis can have social and psychological consequences for the development of children, and because moderate to severe dental fluorosis affects the mechanical properties of teeth, making them vulnerable to chipping or breaking, California has maintained that dental fluorosis is not merely a cosmetic problem. In 1987, US EPA promulgated a MCL of 4 mg/l for fluoride, but California has maintained its temperature-dependent MCL to protect against mottling of the teeth in children.

Fluoride exists naturally in small amounts in most soil but wells dug in fluoride-containing rock formations can contain high levels of fluoride in drinking water. In Southern California, several water districts are exempted by law from the state fluoride primary drinking water standard, i.e., the Big Bear City Community Services District, the Twenty-nine Palms Water District, the Kinneola Irrigation District, and the Riverdale Public Utility District. The statutes allow these water districts to have fluoride in their drinking water at a maximum of 75% of the US EPA's MCL, or 3 mg/l, whichever is higher, for a period of up to 30 years. They were enacted because these communities have no alternate source of drinking water and remedial action would presumably incur an unacceptable financial burden on the communities.

(iv) Radon

In indoor environments, exposure to radon can occur by the direct ingestion of drinking water or, more significantly, through the inhalation route after radon is volatilized from tap water or seeps into living spaces from soil and bedrock located directly beneath the house foundation.

The US EPA has estimated the relative lung cancer risk from radon using epidemiologic data obtained from groups of smoking, underground metal ore miners to be $4.9 \times 10^{-7}/\text{pCi}/\text{l}_w$ and $1.5 \times 10^{-7}/\text{pCi}/\text{l}_w$, via the inhalation and ingestion routes, respectively [18]. Based on this, US EPA, in 1991, proposed a MCLG of zero and a MCL of 300 pCi/l_w for radon, and classified it as a group A human carcinogen. Cancer risk from radon shows a strong multiplicative effect with cigarette smoking. US EPA based its 300 pCi/l_w MCL on risk to an average population of former and light smokers whereas risks to non-smokers are only 20% of the average smokers risk. The risks of lung cancer due to radon exposure in the general population are probably overestimated by US EPA since smoking is on the decline in many areas.

At present, radon in homes is estimated to account for as many as 40 000 lung cancer deaths in the US annually, but with only 1–5% of the deaths attributed to radon in drinking water [18,19]. Although US EPA is required under the 1986 amendments to the Safe Drinking Water Act to regulate radon and other radionuclides in drinking water, it was not given any legal authority to regulate the much higher risk of radon in indoor air. Water utilities are concerned that the proposed regulation, which will be expensive to implement, is only reducing a minor portion of the overall risks from radon exposure, while the main risk from radon in homes remains unregulated. However, ingested radon alone represents a significant cancer risk when compared to many other regulated organic water contaminants.

In California, radon contamination in ground water is found in wells adjacent to radon rock formations of granite, sandstone or feldspar, as commonly occurred in the San Joaquin Valley. Based on aquifer geology, the greatest potential of radon occurrences in ground water (1000–10000 pCi/l_w) is in the counties of Alpine, Amador, Calaveras, El Dorado, Fresno, Kern, Madera, Mariposa, Riverside, San Diego, Tulare, and Tuolumne [20]. Overall, the coastal areas of California contain few locations that have elevated radon contamination of ground water. Using data from the Geographic Information System (GIS) study, it was estimated that 18% of the surveyed large water system wells (7754 wells) and 26% of the surveyed small water system wells (5589) have radon levels at or above 500 pCi/l_w. All of these surveyed large and small water system wells have levels of radon exceeding 200 pCi/l_w. It is estimated that in California, more than 7000 large and small water system wells will be out of compliance with the proposed radon rule [20].

3.2. Surface water

The California State Water Project (SWP) provides drinking water to over 20 million people in northern and southern California. The SWP has 27 lakes and reservoirs which impound 6.8 million acre feet of water, providing municipal and industrial (M&I) and agricultural water supply, flood control, hydroelectric power

generation, recreation, fish and wildlife preservation, and water quality control. Drinking water which is destined for Southern California, is pumped from the South Delta into the California Aqueduct, and stored in four terminal reservoirs for delivery to southern water supply agencies.

The Central Valley Project (CVP) operated by the US Bureau of Reclamation also pumps water from the Delta, but its primary purpose is to provide water for agriculture in the Central Valley. However, due to the Reclamation Projects Authorization and Adjustment Act of 1992, CVP water could now be transferred outside its service area, which could give many metropolitan areas an alternate source of drinking water.

The quality of the water in the Delta is affected by discharges in the watersheds of the Sacramento and San Joaquin Rivers and seawater intrusion from the San Francisco Bay. With increasing urbanization of the Central Valley, especially in areas near the Delta, urban runoff discharges into the Delta have increased in recent years. Key contaminants in urban runoff are sediment, heavy metals and petroleum hydrocarbons. Agricultural drainage contributes pesticides, herbicides, metals (including selenium) and nutrients to the SWP system. Most agricultural discharges are seasonal and/or episodic and are related to specific crop practices. Other sources of contamination to the SWP include seasonal mine discharges (heavy metals, asbestos, mercury and cyanide), seawater intrusion (sodium, chloride, bromide), and others such as highway and canal roadside drainage, pipelines overcrossings, illegal dumping, and accidental spills [21, 22].

3.2.1. Pesticides and synthetic organic chemicals

Pesticides and synthetic organic chemicals have not been a problem in Delta water. Monitoring by the CDWR between 1983 and 1990 found 24 agricultural pesticides at concentrations marginally above detection levels and none above drinking water standards [28, 29]. In this monitoring program, pesticide sampling periods were selected to coincide with summer pesticide application, winter surface water runoff, and spring preemergent herbicide application, so that there was higher likelihood of the pesticides being found at the monitoring sites.

3.2.2. Selenium

Selenium, a known contaminant discharged from agricultural drainage, is monitored in Delta water because of concerns arising from the 1984 Kesterson National Wildlife Refuge episode in which low hatchability and deformities in young aquatic birds were attributed to high selenium levels from agricultural drain water. Although selenium is an essential nutrient to animals and humans at low levels of intake, it is toxic at high levels of exposure. Toxicity in humans include nail changes, and hair loss, skin lesions and neurological effects.

Selenium-laden agricultural drain waters enter the San Joaquin River between February and March each year [21]. During this period, elevated levels can be traced down the San Joaquin River and through the Southern Delta. In monitoring studies conducted by CDWR during this runoff period, the highest levels were found in the lower San Joaquin River. The highest level measured was 3 mg/l in the Delta

Mendota Intake, Banks Delta Pumping plant, and at Vernalis [21]. Due to dilution and natural removal processes, selenium does not currently appear to constitute a health threat to consumers of drinking water pumped from the South Delta, although the possibility of future impacts should not be dismissed.

3.2.3. *Asbestos*

Asbestos (chrysotile) in water arises from the erosion of serpentine rock, which is commonly found in California. Although asbestos is a human carcinogen through inhalation exposure, based on evidence from National Toxicology Program (NTP) dietary ingestion studies [23, 24] of asbestos, asbestos in water is classified by US EPA as a Category II contaminant (limited evidence of carcinogenicity via ingestion). The State of California has adopted the US EPA's MCL for asbestos of 7.1 million fibers per liter of water for fibers 10 μm or greater in length. Asbestos concentrations in raw Delta water vary from 12 million to 7500 million fibers (short and long fibers combined) per liter of water [21, 25]. Treated Delta water rarely contains asbestos concentrations exceeding the drinking water standard. Normal water treatment processes of the raw water, like coagulation, sedimentation, and filtration, generally remove at least 99% of the asbestos [26].

3.2.4. *Trihalomethanes (THMs)*

One major issue of concern with regard to the use of Delta water for drinking is the formation of trihalomethanes (THMs). These are formed when certain organic substances present in the water combine with the chlorine used to disinfect drinking water. In the Delta, the total THM formation potential for water is generally lower at freshwater stations (e.g., American River and Green's Landing) than in the central Delta stations (e.g., Rock Slough and Mallard Island) [27]. The peat soils of the Delta islands are major contributors of organic precursors for the formation of THMs. Organic THM precursors also come from a variety of sources, including agricultural drainage, surface runoff (including urban storm water runoff), wastewater treatment plant discharge, seawater intrusion and algae [27, 28]. Bromides from seawater or estuarine water are also important contributors to THM formation [27]. In general, untreated water supplies from the Delta have total THM formation potential values 3 to 9 times higher than the THM standard for treated water [27].

The most common THM compounds formed during chlorination are chloroform, bromodichloromethane, chlorodibromomethane, and bromoform. With the exception of chlorodibromomethane (placed in Group C), the other THM compounds are classified by US EPA as probable human carcinogens (Group B2). All of these compounds are currently treated by the State of California as probable human carcinogens. Other chlorinated by-products identified include various haloacids, haloaldehydes, halo ketones, haloacetonitriles, chloropicrins, and chlorophenols. Only a few of the compounds in these chemical groups have been sufficiently characterized toxicologically as to their potential human health effects. Current toxicological data for many of these chlorinated by-products are summarized by Bull and Koofler [29] and NAS [30].

At present, water utilities must reduce the total concentration of THMs to 100 mg/l to meet current state and federal drinking water standards. The US EPA is in the process of developing new comprehensive regulations to control disinfectants and disinfection by-products (DBPs). These new standards will possibly include standards for individual THMs, total THMs and other DBPs, and possibly also a new standard for total organic carbon (TOC) in pretreated source waters. The new standards arise primarily from an increasing concern about the reported risks of bladder, rectal and possibly other cancers in humans associated with THMs and DBPs in drinking water treated with chlorine [31]. In establishing the new rule, US EPA has chosen to use the negotiated rule making process to achieve a workable standard. By going through this process, the US EPA is trying to balance the risks involved with disinfection and its by-products with the additional costs and risks of waterborne disease.

The major challenge for water utilities is to sustain a high level of disinfection while minimizing the formation of by-products of disinfection that may be potentially harmful. Currently, treatment technologies are inadequate to reduce the level of DBPs in treated Delta water to meet anticipated drinking water standards. Options that are being studied include using different treatment processes, the removing of precursors by pretreatment of source waters, modifying water conditions (e.g. pH), preventing overtreatment with disinfectant, and direct removal of the DBPs themselves.

4. California's drinking water program

Historically, California has taken the enforcement of drinking water standards very seriously, promulgating its own regulations under the California Safe Drinking Water Act (CSDWA), which are frequently more stringent than the federal regulations. The CDHS has primary enforcement responsibilities, for water systems with 15 or more service connections. Section 4026 (a) of the CSDWA requires the CDHS to promulgate drinking water standards, MCLs and action levels (ALs). The state MCLs are legally enforceable and are based on health effects with adjustments made for technical feasibility, analytical detection limits, and treatment costs. ALs are health-based interim standards for contaminants found in California water supplies for which a MCL has yet to be established. Although ALs are not legally enforceable, they are often adhered to by water providers. MCLs are calculated for single chemicals and do not take into consideration toxicological interactions of chemical mixtures. Further, MCLs are derived for drinking water only and are not intended to be used as target levels for the clean-up of contaminated environmental waters.

The 1989 revision to the CSDWA (AB 21) requires the development of Recommended Public Health Levels (RPHLs) in addition to MCLs for drinking water contaminants. RPHLs are based solely on health effects without regard to cost impacts or other factors. It must also consider possible effects resulting from the interaction of two or more contaminants, sensitive individuals, pharmacokinetics, and the contribution from media other than drinking water. AB 21 requires MCLs to be reviewed every five years after adoption, and the RPHLs to be 'periodically revised as necessary

based upon the availability of new scientific data'. RPHLs apply only to public water systems which have more than 10000 service connections. These systems must reduce the level of contaminants in drinking water to as close to the RPHL as feasible. At the moment, analytical method detection limits for many of the contaminants appear to be one of the important limiting factors for the implementation of RPHLs. The basic underlying philosophy behind the AB 21 legislation is that all water providers must meet the enforceable MCLs, but since this is a risk management level, they should try to remove as much of the contaminants from drinking water as possible, taking into account economical and technical feasibility. RPHLs are similar in many ways to the federal MCLGs, except that for carcinogens they are not set at zero, but at the 10^{-6} lifetime extra risk level.

The current National Primary Drinking Water Regulations (US EPA MCLs) and California's proposed RPHLs and MCLs are shown in Table 3. Proposed RPHLs have been developed for more than 75 chemicals and many of these are scheduled for promulgation in 1993-1994.

Table 3
Proposed and current California and Federal Primary Drinking Water Standards for chemical contaminants

| Chemical | Proposed OEHHA RPHL (mg/l) | CDHS MCL (mg/l) | US EPA MCL (mg/l) |
|--------------------------------------|----------------------------------|-----------------------|-------------------------|
| <i>Inorganics</i> | | | |
| Aluminum ^b | 0.6 | 1 | — |
| Antimony | 0.006 | 0.006 | 0.006 |
| Arsenic | 0.000002 | 0.05 | 0.05 |
| Asbestos | 7MFL ^e | 7MFL ^e | 7MFL ^e |
| Barium | 0.6 | 1 | 2 |
| Beryllium | 0.004 | 0.004 | 0.004 |
| Cadmium | 0.005 | 0.005 | 0.005 |
| Chlorate | 0.002 | — | — |
| Chlorite | 0.002 | — | — |
| Chromium (total) | 0.002 | 0.05 | 0.1 |
| Copper | 0.2 | — | 1.3 ^d |
| Cyanide | 0.2 | 0.2 | 0.2 |
| Fluoride | — | 1.4-2.4 | 4 |
| Lead | 0.001 | — | 0.015 ^d |
| Mercury | 0.002 | 0.002 | 0.002 |
| Nickel | 0.1 | 0.1 | 0.1 |
| Nitrate as N | 10 | 10 | 10 |
| Nitrite as N | 1 | 1 | 1 |
| Total nitrate/nitrite | — | 10 | 10 |
| Selenium | 0.05 | 0.05 | 0.05 |
| Thallium | 0.0005 | 0.002 | 0.002 |
| <i>Volatile organic chemicals</i> | | | |
| Benzene | 0.0004 | 0.001 | 0.005 |
| Carbon tetrachloride | 0.0005 | 0.0005 | 0.005 |
| Chlorine dioxide | 0.02 | — | — |
| 1,2-Dichlorobenzene (<i>o</i> -DCB) | 0.6 | 0.6 | 0.6 |
| 1,4-Dichlorobenzene (<i>p</i> -DCB) | 0.001 | 0.005 | 0.075 |

Table 3
(Continued)

| Chemical | Proposed OEHHA RPHL (mg/l) | CDHS MCL (mg/l) | US EPA MCL (mg/l) |
|---|----------------------------------|-----------------------|-------------------------|
| 1,1-Dichloroethane | 0.005 | 0.005 | — |
| 1,2-Dichloroethane (1,2-DCA) | 0.0003 | 0.0005 | 0.005 |
| 1,1-Dichloroethylene | 0.006 | 0.007 | 0.007 |
| Cis-1,2-dichloroethylene (cis-1,2-DCE) | 0.006 | 0.006 | 0.07 |
| Trans-1,2-dichloroethylene | 0.01 | 0.01 | 0.01 |
| Dichloromethane (methylene chloride) | 0.003 | 0.005 | 0.005 |
| 1,2-Dichloropropane (1,2-DCP) | 0.005 | 0.005 | 0.005 |
| 1,3-Dichloropropene (Telone) | 0.0002 | 0.0005 | — |
| Ethylbenzene | 0.68 | 0.7 | 0.7 |
| Monochlorobenzene (chlorobenzene) | 0.07 | 0.07 | 0.1 |
| Styrene | 0.1 | 0.1 | 0.1 |
| 1,1,2,2-Tetrachloroethane | 0.001 | 0.001 | — |
| Tetrachloroethylene (perchloroethylene, PCE) | 0.0007 | 0.005 | 0.005 |
| Toluene | 0.15 | 0.15 | 1 |
| 1,2,4-Trichlorobenzene (trichlorobenzene) | 0.07 | 0.07 | 0.07 |
| 1,1,1-Trichloroethane | 0.2 | 0.2 | 0.2 |
| 1,1,2-Trichloroethane (1,1,2-TCA) | 0.001 | 0.005 | 0.005 |
| Trichloroethylene (TCE) | 0.0008 | 0.005 | 0.005 |
| Trichlorofluoromethane (Freon 11) | 0.15 | 0.15 | — |
| 1,1,2-Trichloro-1,2,2-trifluoroethane (Freon 113) | 1.2 | 1.2 | — |
| Vinyl chloride | 0.0002 | 0.0005 | 0.002 |
| Xylenes ^f | 1.75 | 1.75 | 10 |
| <i>Synthetic organic chemicals</i> | | | |
| Acrylamide | — | — | Trmt. tech. |
| Alachlor | 0.0004 | 0.002 | 0.002 |
| Aldicarb | 0.00008 ^c | — | 0.003 ^c |
| Aldicarb sulfone | — | — | 0.002 ^e |
| Aldicarb sulfoxide | 0.0008 ^c | — | 0.004 ^e |
| Atrazine | 0.003 | 0.003 | 0.003 |
| Bentazon | 0.018 | 0.018 | — |
| Benzo(a)pyrene | 0.000002 | 0.0002 | 0.0002 |
| Carbofuran | 0.018 | 0.018 | 0.04 |
| Chlordane | 0.00003 | 0.0001 | 0.002 |
| Dalapon | 0.2 | 0.2 | 0.2 |
| 1,2-Dibromo-3-chloropropane (DBCP) | 0.000002 | 0.0002 | 0.0002 |
| 2,4,-Dichlorophenoxyacetic acid (2,4-D) | 0.07 | 0.07 | 0.07 |
| Di(2-ethylhexyl) adipate (DEHA) | 0.4 | 0.4 | 0.4 |
| Di(2-ethylhexyl) phthalate (DEHP) | 0.004 | 0.004 | 0.006 |
| Dinoseb | 0.007 | 0.007 | 0.007 |
| Diquat | 0.015 | 0.02 | 0.02 |
| Endothall | 0.1 | 0.1 | 0.1 |
| Endrin | 0.002 | 0.002 | 0.002 |
| Epichlorohydrin | — | — | Trmt. tech. |
| Ethylene dibromide (EDB) | 0.00001 | 0.00002 | 0.00005 |
| Glyphosate | 0.7 | 0.7 | 0.7 |
| Heptachlor | 0.00001 | 0.00001 | 0.0004 |
| Heptachlor epoxide | 0.000007 | 0.00001 | 0.0002 |
| Hexachlorobenzene | 0.00002 | 0.001 | 0.001 |

(Continued on next page)

Table 3
(Continued)

| Chemical | Proposed OEHHA RPHL (mg/l) | CDHS MCL (mg/l) | US EPA MCL (mg/l) |
|--|----------------------------------|-----------------------|-------------------------|
| Hexachlorocyclopentadiene (HEX) | 0.05 | 0.05 | 0.05 |
| Lindane | 0.00004 | 0.0002 | 0.0002 |
| Methoxychlor | 0.04 | 0.04 | 0.04 |
| Molinate | 0.02 | 0.02 | — |
| Oxamyl (Vydate) | 0.2 | 0.2 | 0.2 |
| Pentachlorophenol (PCP) | 0.0002 | 0.0003 | 0.001 |
| Picloram | 0.5 | 0.5 | 0.5 |
| Polychlorinated biphenyls (PCBs) | 0.000007 | 0.0005 | 0.0005 |
| Simazine | 0.004 | 0.004 | 0.004 |
| Thiobencarb (Bolero) | 0.07 | 0.07 | — |
| Toxaphene | 0.00003 | 0.003 | 0.003 |
| 2,3,7,8-TCDD (dioxin) | 2×10^{-10} | 3×10^{-8} | 3×10^{-8} |
| 2(2,4,5-Trichlorophenoxy) propionic acid (2,4,5-TP, Silvex) | 0.05 | 0.05 | 0.05 |
| Trihalomethanes (total) | — | 0.1 | 0.1 |

| Chemical | Proposed OEHHA RPHL (pCi/l) ^g | CDHS MCL (pCi/l) | US EPA MCL (pCi/l) ^h |
|---|---|------------------------|---------------------------------------|
| <i>Radionuclides</i> | | | |
| Adjusted gross alpha emitters (excluding Ra-226, U, and Rn-222) | Polonium: 0.14 Thorium: 0.5 Plutonium: 0.07 | 15 | 15 |
| Beta particle and photon emitters (excluding Ra-228) | 0.04 mrem ede/yr ^h | 50 | 4 mrem ede/yr ^h |
| Radium-226 | 0.22 | 5 ⁱ | 20 |
| Radium-228 | 0.26 | 5 ⁱ | 20 |
| Radon-222 | 1.5 | — | 300 |
| Strontium-90 | — | 8 | — |
| Tritium | 1.7 | 20 000 | — |
| Uranium | 1.7 (1.2 µg/l) | 20 | 30 (20 µg/l) |

^a Source: CDHS (1992) and US EPA (1993).

^b US EPA removed chemical from the list of the original 83 contaminants mandated for regulation under the SDWA of 1986.

^c MFL = million fibers per liter, with fiber length > 10 µm.

^d Action level.

^e Proposed.

^f MCL is for either single isomer or the sum of the isomers.

^g pCi/l = pico Curies per liter.

^h mrem ede/yr = millirem effective dose equivalent per year.

ⁱ Combined Ra-226 and Ra-228.

5. Toxicological risk assessment

The assessment of health risk and safe exposures to substances in drinking water has been described in various publications [32-35]. The purpose of this section is to outline the scientific process by which risk to humans can be estimated and to provide information on how this is used for the setting of drinking water standards. The Office of Environmental Health Hazard Assessment (OEHHA), Cal/EPA, is given the responsibility for performing risk assessment of drinking water contaminants. The review and evaluation of toxicology, epidemiology, metabolism and exposure data are conducted in-house by OEHHA staff and consultants. All contracted health risk assessments, usually performed within the University of California system or affiliated National Laboratories, are subjected to two external peer reviews. In all cases the development of rationales supporting the health-based drinking water standards is conducted by OEHHA staff.

5.1. Non-carcinogens

In general the risk assessment of non-carcinogens follows guidelines that are used by US EPA and NAS [35, 36]. For non-carcinogens the evaluations resulted in identification of a suitable no-observable-adverse-effect level (NOAEL) or lowest-observable-adverse-effect level (LOAEL) values. For volatile organics the evaluation includes an assessment of exposure via non-ingestion routes such as inhalation and dermal exposures resulting from typical household activities (showering, bathing, flushing toilets, etc.) [37, 38]. The initial proposed MCL (PMCL) or RPHL values are usually derived by the following relation:

$$\text{PMCL (mg/l) or RPHL} = \frac{(\text{NOAEL/LOAEL, mg/kg d}) (70 \text{ kg}) (\text{RSC})}{(\text{UF}) (W, \text{ l/d})}$$

where NOAEL or LOAEL values are in mg/kg d; 70 kg is the standard human body weight. RSC is the relative source contribution, usually assumed to be 20% or 0.2 if adequate data on other sources of human exposure are absent, or 100% if water is believed to be the likely sole source. UF is the overall uncertainty factor or the product of 10-fold uncertainty factors reflecting the quality of data on which the NOAEL or LOAEL is based. Guidelines for selection of uncertainty factors are similar to that suggested by Dourson and Stara [39] and used by the US EPA [35]. *W* is the estimated daily water consumption of 2 l/d for drinking water only (oral) exposure and larger l equivalents/d for volatile organics subject to inhalation and dermal exposures.

To determine the maximum contaminant level goal (MCLG) for non-carcinogens, the US EPA is now utilizing a 20% default assumption in calculating drinking water contributions when relative source contribution (RSC) data are lacking or where data indicate that drinking water contributes 20% or less of the total exposure. Where data indicate drinking water exposure is between 80 and 100% of total exposure to a contamination, a RSC for drinking water of up to 80% is assigned. While 80% may be a more realistic ceiling since it is difficult to be certain that 100% of exposure to any

chemical comes solely from drinking water, 20% may be too high for a minimum contribution and its use could lead to numerically excessive MCLGs. OEHHA has remained flexible on setting the RSCs and will evaluate each contaminant on its own merit.

In 1991, US EPA issued guidance recommending that 'when time, resources, or other constraints prevent the use of monitoring or modeling data, risk assessors should assume that exposure to volatile chemicals during showering is equivalent to exposures from ingesting two liters of same water per day' [40]. OEHHA has advocated the use of monitoring data and modeling techniques to estimate likely human exposures via alternate routes of exposure to volatile compounds in drinking water, and has used these estimates in establishing human health-based drinking water standards for California for many years. In our experience estimated human exposures from these additional routes for VOCs could range from 3 to 10 times that by the ingestion route depending on the individual chemical and other environmental and human behavioral factors. Thus, while providing a useful default assumption, the agency's conclusion that contribution from other routes of exposure is equivalent to exposure from ingesting 2 l/d of the contaminated water may underestimate human exposure and the associated risk for adverse human health effects in some cases.

At the moment, OEHHA is examining the use of benchmark doses instead of NOAELs in the risk assessment of non-carcinogens. This approach is also being evaluated by US EPA but they have indicated that at present there is insufficient experience with the application of this approach to use it for calculating the reference dose (RFD). Issues concerning the use of the benchmark dose for non-carcinogens are discussed in various publications [41, 42].

5.2. Carcinogens

The guidelines currently used by OEHHA to identify and assess the risks of carcinogens are documented in the CDHS Guidelines for Chemical Carcinogen Risk Assessment and Their Scientific Rationale (1985) [43]. The CDHS guidelines are similar in many ways to those adopted by the US EPA in 1986 [44]. For water contaminants that have the potential to cause cancer in humans the relationship between risk and exposure can be determined. In these studies where excess cancer risk has been associated with exposure to a chemical, the estimated human potency can be derived directly from the epidemiological data. But, these types of data are rarely available or adequate for cancer risk assessment. When animal studies are used, the human potency estimate can be derived using the linearized multistage model fitted to the animal tumor incidence data.

This default approach uses the 95% upper-bound estimate of the low dose slope extrapolated from dose-response data, and assumes that the upper bound on slope or the potency is linear at very low doses. To extrapolate potency (q_1^*) derived from animal data ($q_1^*(A)$) to humans ($q_1^*(H)$) a conversion based on the surface area or (body weight)^{2/3} is used:

$$q_1^*(H) = q_1^*(A)(W_H/W_A)^{1/3},$$

where W_H is the standard human body weight in kg, W_A is the animal weight in kg, $q_1^*(A)$ is the animal potency in $(\text{mg/kg d})^{-1}$, $q_1^*(H)$ is the human potency in $(\text{mg/kg d})^{-1}$.

The cube root of the body weights ratio adjusts for species differences with the assumption that metabolic rate is proportional to the 2/3 power of body weight [45]. In fitting the linearized multistage model to the animal cancer data, actual dosing data are converted to daily average lifetime doses. When available, other dose metrics which include pharmacokinetic behavior are also taken into account. In cases of reduced study duration the potency values are converted for intercurrent mortality by the factor $(L/Le)^3$ where Le is the duration of the experiment and L is the life span of the animal, usually 105 weeks. US EPA is currently proposing the use of a cross-species scaling factor for carcinogen risk assessment based on equivalence of $\text{mg/kg}^{3/4} \text{ d}$ [46]. This is currently under evaluation by OEHHA.

The PMCL or RPHL derived for a carcinogen is determined by the following equation:

$$\text{PMCL (mg/l) or RPHL} = \frac{(\text{Risk}) (70 \text{ kg}) (\text{RSC})}{[q_1^*(H) (\text{mg/kg d})^{-1} (W, \text{l/d})]}$$

where Risk is the de minimus individual extra lifetime cancer risk of 10^{-6} , RSC is the relative source contribution often, but not always, assumed to be 1.0, W is the water consumption in l/d or l equivalent/d if additional exposure routes are considered.

The potency estimates calculated by OEHHA occasionally differ from those adopted by US EPA. Differences are mainly attributed to study or data set selection, averaging of potencies by arithmetic or geometric means and the use of different exposure estimates particularly with regard to volatile organic compounds.

6. Risk management and standard setting process

The public health-based regulatory activities can be viewed as based on two parts: risk assessment, described earlier, which is the use of scientific data to define the human health effects from exposure to hazardous materials, and risk management, the process towards a decision about control using the risk assessment information provided. The National Academy of Sciences [47] defined risk management as the 'complex of judgment and analysis that uses the results of risk assessment to produce a decision about environmental action'. This definition was originally intended to distinguish the political, economic, and social aspects of decision-making from the scientific exercise involved in the assessment of risk but it now embodies a much broader concept, involving resources, priorities, policies and other themes [47]. Thus, the nature of risk management activity will depend on the environment in which it occurs, that for a corporate industry will differ from that of a federal or state regulatory agency.

In California, the risk management of the health-based drinking water level (RPHL or PMCL) to derive the drinking water standard (MCL) is the intermediary step between the risk assessment and the adoption of the MCL with which state public

drinking water systems must comply. The risk management process attempts to balance the public health benefits to be derived from regulating a contaminant at various levels with the analytical and technical feasibility and costs of meeting those levels. Benefits include reduction of actual or potential adverse human health effects, but can also include reduction of the risk of such effects and reduction in the population exposed to the effects of the risk. Quantifiable costs include the monetary expenditures to monitor and mitigate the risk. Feasibility involves an evaluation of the available analytical methodology and treatment technology, as well as a comparison of the analytical detection limits with the proposed standards.

The OEHHA's RPHL or PMCL is the risk assessment result used as input to the risk management process. Based on the risk assessment and available data on drinking water contamination, the CDHS estimates the extent of exposure and adverse health effects in the state. For a RPHL or PMCL to be technically feasible as a standard (MCL), approved analytical methodology must exist, the detection limit must be less than or equal to the PMCL, and there must be technology for removal of the chemical from the drinking water sources contaminated with a chemical which is a carcinogen. A matrix is developed of estimated costs for monitoring and treatment (based on available monitoring data, US EPA studies, and contamination projections) versus the number of estimated excess cancer cases and the population exposed at the 10^{-4} , 10^{-5} and 10^{-6} 'acceptable risks levels'. This matrix is used to determine the most reasonable MCL in terms of public health protection and cost.

Generally, the risk management process for a non-carcinogen is simpler, involving primarily a consideration of technical feasibility. The reason is the difference in the nature of the RPHLs or PMCLs. In the case of carcinogens, MCLs have historically been adopted within the range of 10^{-6} to 10^{-4} 'acceptable risks levels'. However, the derivation of the RPHL or PMCL for a non-carcinogen differs since it incorporates uncertainty factors and does not include an 'acceptable risk level' which can vary. Hence, the MCL for a non-carcinogen is typically proposed at the RPHL or PMCL level unless there are technical reasons for not doing so.

The drinking water adoption process involves a number of steps, the first being the development of a regulatory package which includes not only the proposed regulations themselves, but also a description, justification and cost estimate for the chemicals to be regulated. The package is then submitted to internal CDHS review for regulatory consistency, state budget impact, and legal issues. Next it goes to the State Department of Finance for a comprehensive review of the fiscal impact of state agencies. A public hearing is then held, public comments respond to and regulatory changes made if appropriate. If necessary a second public hearing may be held. It is then examined by the State Office of Administration Law for technical/legal detail, and this is then signed into regulation by the State Secretary. The process can take from nine months to a year and a half.

References

- [1] California Department of Water Resources (CDWR), California Waters: Looking to the Future, Bulletin No. 160-8, Sacramento, California, 1987.

- [2] State Water Resources Control Board (SWRCB), Water Quality and Pesticides: A California Risk Assessment Program, SWRCB Pub. 84-62P, 1984.
- [3] D.B. Cohen, Ground water contamination by toxic substances: A California assessment, in: W.Y. Garner, R.C. Honeycut and H.N. Niggs (Eds.), Evaluation of Pesticides in Ground Water, ACS Symposium Series 315, American Chemical Society, Washington, DC, 1986, pp. 499–529.
- [4] H.H. Russell, R.J. Jackson, D.P. Spath and S.A. Book, Chemical contamination of California drinking water, *Western J. Med.*, 147 (1987) 615–622.
- [5] California Department of Pesticide Registration (CDPR), Sampling for Pesticide Residues in California Well Water: 1992 Well Inventory Data Base, Cumulative Report 1986–1992, CDPR, Sacramento, 1992.
- [6] California Department of Health Services (CDHS), Organic Chemical Contamination of Large Public Water Systems in California, CDHS, 1986.
- [7] California Department of Health Services (CDHS), Organic Contamination of Small Public Water Systems in California, CDHS, 1990.
- [8] L.A. Smith, K.P. Green and D.M. Mackay, Quality of groundwater in California: Overview and implications, in: *Coping with Water Scarcity: The Role of Ground Water*, Seventeenth Biennial Conference on Ground Water, San Diego, California, Report No. 72, 1990, pp. 93–107.
- [9] National Academy of Sciences (NAS), Nitrates: An Environmental Assessment, NAS, Washington, DC, 1978.
- [10] A.M. Fan, C.C. Willhite and S.A. Book, Evaluation of nitrate drinking water standard with specific references to methemoglobinemia and reproductive toxicity, *Regul. Toxicol. Pharmacol.*, 7 (1987) 135–148.
- [11] D.P. Spath, The nitrate threat, in: *Coping with Water Scarcity: The Role of Ground Water*, Seventeenth Biennial Conference on Ground Water, San Diego, California, Report No. 72, 1990, pp. 149–155.
- [12] C.J. Chen, Y.C. Chuang, S.L. You, T.M. Lin and H.Y. Wu, A retrospective study of malignant neoplasms of bladder, lung and liver in Blackfoot disease endemic area in Taiwan, *Br. J. Cancer*, 53 (1986) 399–405.
- [13] C.J. Chen and C.J. Wang, Ecological correlation between arsenic level in well water and age-adjusted mortality from malignant neoplasms, *Cancer Res.*, 5C (1990) 5470–5474.
- [14] A.H. Smith, C. Hopenhayn-Rich, M.N. Bates, H.M. Goeden, I. Hertz-Picciotto, H.M. Duggan, R. Wood, M.J. Kosnett and M.T. Smith, Cancer risks from arsenic in drinking water, *Environ. Health Perspect.* 97 (1992) 259–267.
- [15] A.H. Smith, H. Goeden, V. Shearn, M. Bates and M.T. Smith, Health Risk Assessment for Arsenic Ingestion, Health Risks Associates, Berkeley, CA, 1990.
- [16] J.P. Brown and A.M. Fan, Arsenic: Recommended Public Health Level for Drinking Water, Office of Environmental Health Hazard Assessment, Berkeley, 1992.
- [17] P.A. Rogers, Implementing Assembly Bill 21: New modes of regulation, in: *Protecting Drinking Water Quality at the Source*, University of California, Water Resources Center, Riverside, CA, 1991, pp. 95–99.
- [18] Federal Register, US Environmental Protection Agency, National Primary Drinking Water Regulation: Radionuclides, Proposed Rules, *Federal Register*, 56 (138) (1991) 33050.
- [19] National Academy of Sciences (NAS), Health Effects of Exposure to Low Levels of Ionizing Radiation, BEIR V, National Academy Press, Washington, DC, 1990.
- [20] R.H. Sakaji, Radon in California's Groundwater: A Water Quality Survey and Exposure Assessment, Office of Drinking Water, California Department of Health Services, Berkeley, CA, 1991.
- [21] California Department of Water Resources (CDWR), The Delta as a Source of Drinking Water, Monitoring Results, 1983 to 1987, Interagency Delta Health Aspects Monitoring Program, CDWR, 1989.
- [22] California Department of Water Resources (CDWR), Delta Island Drainage Investigation Report of the Interagency Delta Health Aspects Monitoring Program, CDWR, 1990.
- [23] National Toxicology Program (NTP), Toxicology and Carcinogenesis Studies of Chrysotile Asbestos in F344/N Rats (Feed Studies), NTP Technical Report Series No. 295, 1985.

- [24] National Toxicology Program (NTP), Lifetime Carcinogenesis Studies of Chrysotile Asbestos in Syrian Golden Hamsters (Feed Studies), NTP Technical Report Series No. 246, 1983.
- [25] R.C. Bales, D.D. Newkirk and S.B. Hayward, Chrysotile asbestos in California surface water: From upstream rivers through water treatment, *J. Am. Water Works*, 76 (1984) 76–82.
- [26] M.J. McGuire, A.E. Bowers and D.A. Bowers, Optimizing large-scale water treatment plants for asbestos fiber removal, *J. Am. Water Works*, 75 (1983) 364–369.
- [27] State of California, Delta Water Quality: A Report to the Legislature on Trihalomethanes and the Quality of Drinking Water Available from the Sacramento–San Joaquin Delta, SWRCB, CDHS and CDWR, 1991.
- [28] State Water Resources Control Board (SWRCB), Water Quality Assessment 1991, SWRCB, 1992.
- [29] R.J. Bull and F.C. Kopfler, Health Effects of Disinfectants and Disinfection By-Products, American Water Works Association Research Foundation, Denver, 1991.
- [30] National Academy of Science (NAS), Disinfectants and disinfectant by-products, in: *Drinking Water and Health*, Vol. 7, National Academy Press, Washington, DC, 1987.
- [31] R.D. Morris, A.M. Audet, I.F. Angelillo, T.C. Chalmers and F. Mosteller, Chlorination, chlorination by-products, and cancer: A meta-analysis, *Am. J. Public Health*, 82 (1992) 955–963.
- [32] US Environmental Protection Agency (US EPA), Workshops on Assessment and Management of Drinking Water Contamination, US EPA/Office of Water, Washington, DC, EPA/600/M-86/026, 1987.
- [33] National Academy of Sciences (NAS), Risk assessments, in: *Drinking Water and Health*, Vol. 6, National Academy Press, Washington, DC, 1986, pp. 250–293.
- [34] National Academy of Sciences (NAS), Pharmacokinetics in risk assessment, in: *Drinking Water and Health*, Vol. 8, National Academy Press, Washington, DC, 1987.
- [35] US Environmental Protection Agency (US EPA), Risk Assessment Management and Communication of Drinking Water Contamination, US EPA/Office of Water, Washington, DC, EPA/625/4-89/024, 1990.
- [36] National Academy of Sciences (NAS), Chemical contaminants: Safety and risk assessment, in: *Drinking Water and Health*, Vol. 1, National Academy Press, Washington, DC, 1977, pp. 19–62.
- [37] T.B. McKone, Human exposure to volatile organic compounds in household tap water: The indoor inhalation pathway, *Environ. Sci. Technol.*, 21 (1987) 1194–1201.
- [38] H.S. Brown, D.R. Bishop and C.A. Rowan, The role of skin absorption as a route of exposure for volatile organic compounds (VOCs) in drinking water, *Am. J. Public Health*, (1984) 479–484.
- [39] M.L. Dourson and J.F. Stara, Regulatory history and experimental support of uncertainty (safety) factors, *Regul. Toxicol. Pharmacol.*, 3 (1983) 224–238.
- [40] US Environmental Protection Agency (US EPA), Guidance on Estimating Exposure to VOCs During Showering, Memo from Risk Assessment Forum/Office of Research and Development, 10 July 1991.
- [41] B.D. Beck, R.B. Conolly, M.L. Dourson, D. Guth, D. Hattis, C. Kimmel and S.C. Lewis, Symposium overview, improvements in quantitative noncancer risk assessment, *Fundam. Appl. Toxicol.*, 20 (1993) 1–14.
- [42] K.S. Crump and B.C. Allen, The Use of the Benchmark Dose (BMD) Approach in Health Risk Assessment, US EPA/Risk Assessment Forum, 1991.
- [43] California Department of Health Services (CDHS), Guidelines for Chemical Carcinogen Risk Assessment and Their Scientific Rationale, CDHS, Sacramento, CA, 1985.
- [44] US Environmental Protection Agency (US EPA), The Risk Assessment Guidelines of 1986, US EPA, Office of Health and Environmental Assessment, Washington, DC, 1987.
- [45] K.S. Crump, An improved procedure for low dose carcinogenic risk assessment from animal data, *J. Environ. Path. Toxicol. Oncology*, 5 (1984) 339–348.
- [46] Federal Register, A Draft Report: A Cross-Species Scaling Factor for Carcinogen Risk Assessment Based on Equivalence of $\text{mg/kg}^{3/4}/\text{day}$, 5 June 1992.
- [47] National Academy of Sciences (NAS), Risk Assessment in the Federal Government Managing the Process, NAS, Washington, DC, 1983.