NOTE TO USERS

The original manuscript received by UMI contains indistinct, slanted and or light print. All efforts were made to acquire the highest quality manuscript from the author or school. Microfilmed as received.

This reproduction is the best copy available

UMI
Mercury Dynamics in the Lahontan Reservoir: Application of QWASI Fugacity/Equivalence Multispecies Model

by

Murali Ganapathy

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Chemical Engineering and Applied Chemistry
University of Toronto

© Copyright by Murali Ganapathy 1997
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.
Multispecies steady- and unsteady-state models have been developed to describe mercury dynamics in the Lahontan Reservoir on Carson River, Nevada, using the QWASI equivalence approach. The models describe the long term fate of mercury, effects of seasonality, and the dominant processes affecting mercury fate in the reservoir. The models were developed as steady-state snapshots of three times of the year and a time dependent version that integrates the snapshots. Model estimates that over 90% of mercury inputs are retained in the reservoir, the balance being lost through export. Annually, methylmercury is supplied by the Carson River with no significant production occurring in the Reservoir. Hg from deep sediments is hypothesized to enter the system through mixing caused by seasonal wet and dry cycles. The hypothesized Hg mixing in sediments results in Hg remobilization and maintenance of elevated concentrations in the reservoir.
I wish to acknowledge the many individuals who assisted me in this thesis. First and foremost, I wish to express thanks to Dr. M. Diamond who was not only instrumental in my being here at the University of Toronto, but also provided generous support, guidance and encouragement throughout the completion of my thesis.

I have benefited immensely from discussions and information from Carl Mach and Steve Peterson of Ecology and Environment, Inc. and Wayne Preskins of USEPA. I am grateful to Dr. D. Cormack and Dr. C.Q. Jia for being a part of my defense committee. I like to thank J.Briscoe for assisting me with administrative aspects of department graduate studies.

Thanks to my past and present fellow researchers at the university, especially Mehran Monabbati, Neely Law, Paul Helm, and Cynthia Page.

On a more personal level, I wish to thank all my friends for the encouragement they provided during my pursuit of this degree. I am extremely grateful to my wife Sita and my daughter Kritika for not having given up on me and always being there.
1. Introduction

1.1 Mercury as a contaminant
1.2 Lahontan Reservoir Problem Definition
1.3 Modeling Approach and Objectives

2. Mercury Dynamics in Aquatic Systems - A Literature Review

2.1 Hg, its properties and toxicity
2.2 MeHg and Methylation
2.3 Mercury in Lakes and Reservoirs
2.4 Point and Non-point Sources of Hg

3. QWASI Multi-Species Model

3.1 Fugacity and Equivalence Concepts
3.2 Application of the model to Speciating Chemicals
3.3 D Values
3.4 The QWASI Model

4. Lahontan Reservoir Description, Steady-State Model Parameterization and Calibration

4.1 Lahontan Reservoir Description
4.2 Parameterization of steady-state model
  4.2.1 Reservoir Water and Sediment Volumes
  4.2.2 Reservoir Flows
  4.2.3 Sediments
  4.2.4 Suspended Particles and Particle Balance
4.3 Mercury Speciation and Sampling Data
4.4 Steady State Model Formulation
4.5 Mass Balance Equations
4.6 Model Calibration and Testing
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.1</td>
<td>Comparison of Hg concentration in polluted and remote lakes/reservoirs</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>3.1</td>
<td>Processes and rate expressions used in the Lahontan Reservoir model</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>4.1</td>
<td>Deposition rates calculated from sediment traps</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>Reservoir parameters - May 1995.</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>Reservoir parameters - February 1995.</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>Reservoir parameters - September 1994.</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>Mercury species concentration fractions in air, water, and sediment</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>Physical-chemical properties of mercury species</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>Chemical parameters</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>Comparison between measured and estimated water and sediment concentrations</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>Equations used in the unsteady-state model to describe the various time dependent parameters.</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>6.1</td>
<td>Degree and reasons for uncertainties in parameters used in the model</td>
<td>70</td>
</tr>
</tbody>
</table>
List of Figures

Chapter 1

Figure 1.1 Location of the various hydrogeographic areas within the Carson River Drainage Basin. 3

Chapter 2

Figure 2.1 The biogeochemical cycle for mercury. 9

Chapter 3

Figure 3.1 Illustration of compartments and processes considered in the QWASI model for Hg behaviour in one basin of the Lahontan Reservoir. 21

Chapter 4

Figure 4.1 Location of Lahontan Reservoir in Western United States. 23
Figure 4.2 The Lahontan Reservoir. 26
Figure 4.3 Reservoir monthly average volumes. 27
Figure 4.4 Carson River flow during July 1994 to June 1995. 29
Figure 4.5 Mean monthly flow and quartile statistics, Carson River gauge. 29
Figure 4.6 Geologic map of Lahontan Reservoir and Hg concentrations within the geomorphological units. 31
Figure 4.7 Particle balance for May 1995. 34
Figure 4.8 Particle balance for February 1995. 35
Figure 4.9 Particle balance for September 1994. 36
Figure 4.10 Dissolved and particulate fractions of Hg in water. 42
Figure 4.11 Methyl Hg concentrations in the reservoir basins as measured by EPA 1996. 42
Figure 4.12 Comparison of measured and model estimated Hg concentrations in water column. 48
Figure 4.13  Comparison of measured and estimated sediment Hg concentrations.

Chapter 5

Figure 5.1  Comparison of USS model results for finite source and reducing term of buried sediments in middle basin.

Chapter 6

Figure 6.1  Estimated rates of total Hg transport for May 1995.
Figure 6.2  Estimated rates of elemental Hg transport for May 1995.
Figure 6.3  Estimated rates of MeHg transport for May 1995.
Figure 6.4  Estimated rates of residual Hg transport for May 1995.
Figure 6.5  Estimated rates of total Hg transport for February 1995.
Figure 6.6  Estimated rates of MeHg transport for February 1995.
Figure 6.7  Estimated rates of total Hg for September 1994.
Figure 6.8  Sensitivity of Hg water and upper sediment concentrations in south basin to doubling parameters for steady-state model.
Figure 6.9  Estimated Hg concentrations in south basin in water column and sediments illustrating the seasonal variations and the long term behaviour.
Figure 6.10 Estimated Hg concentrations in middle basin in water column and sediments illustrating the seasonal variations and the long term behaviour.
Figure 6.11 Estimated Hg concentrations in north basin in water column and sediments illustrating the seasonal variations and the long term behaviour.
Figure 6.12 Estimated average Hg concentrations in south basin in water column and sediments.
Figure 6.13 Estimated average Hg concentrations in middle basin in water column and sediments.
Figure 6.15 Estimated response of the Lahontan Reservoir north basin to reduction in the Carson River loadings by 50% and 90%.

Figure 6.16 Estimated response of the Lahontan Reservoir south basin to reduction in the Carson River loadings by 50% and 90% and to no buried sediment introduction.

Figure 6.17 Response of water column Hg concentration of south basin to linear reduction in buried sediment Hg concentrations as estimated by the USS model.

Figure 6.18 Estimated response of Hg concentration in north basin to changes to Dam outflow.

Figure 6.19 Estimated response of Hg concentration in north basin to changes in Truckee Canal flow.
1. Introduction

1.1 Mercury as a contaminant

"The morality that pollution is criminal only after legal conviction is the morality that causes pollution" (Smith & Smith 1975). Minamata Disease was the first occurrence of widespread methylmercury (MeHg) poisoning caused by environmental pollution that the world has experienced. Minamata Disease was discovered in 1956 and its cause identified in 1959. Nevertheless, the present situation of the 100,000 persons who live within reach of the original Hg contamination of the environment is still unclear (Harada and Smith 1975).

Hg and its species are among the most highly ranked environmental pollutants of this century. There have been large-scale poisonings in certain populations exposed to food, usually fish, contaminated with Hg e.g., Iraq (Jalili and Abbasi, 1961), Guatemala (Eyl 1971), Minamata among others. In most of these cases, MeHg had bioaccumulated and biomagnified within the fish and consumption of these contaminated fish led to the poisonings. The English-Wabigoon River system (Parks and Hamilton, 1987), Onondaga Lake, New York (Bloom and Effler, 1990) and the Lahontan Reservoir (Richins and Risser, 1972) are other aquatic systems having high Hg concentrations in fish caused by discharges attributable to a point sources such as industrial, urban or mining waste discharges.

Hg cycling in pristine lakes in remote regions of Ontario, Wisconsin, Minnesota, and Sweden also show high Hg concentrations in surface waters and biota, suggested to originate from atmospheric deposition due to anthropogenic activity (e.g., Fitzgerald et al. 1991, Krabbenhof and Babiarz 1992). Thus, the bioconcentration of Hg in fish is not limited by the source of Hg but by its chemistry. MeHg, being the species of concern, is the focus of research. Jensen and Jernelöv (1969) first demonstrated the conversion of inorganic Hg to MeHg in aquarium sediments. Aquatic systems, where conversion to
distribution in aquatic systems are further complicated by the variability of systems
including the limnology of the water body. The amount of organic material, dissolved
oxygen, sulfides and chlorides, temperature variation, pH, and mineralogy of the
particulates play important roles in determining the speciation of Hg and fate and
transport of these species throughout the system.

1.2 Lahontan Reservoir Problem Definition

The Carson River Superfund Site was placed on the National Priorities List for
remediation and restoration by the US Environmental Protection Agency in August 1990
because of elevated levels of Hg in fish, water column and sediments. The contamination
is a legacy of ore processing during the Gold Rush from the Comstock ores mined from
the Virginia Range between 1860 to 1890 (Gustin et al. 1994).

The Carson River watershed basin drains 10,000 square kilometers in east-central
California and west-central Nevada. The Carson River flows through a series of generally
separate alluvial valleys from the headwaters to Carson Sink. In downstream order, the
alluvial valleys passed by the river include Carson Valley, Dayton Plains, Stagecoach
Valley, Churchill Valley, and Carson Desert (Figure 1.1). Between New Empire and
Dayton, the river flows through a narrow stretch along which large ore-processing mills
were situated during the late 1800s. The flow of the river is interrupted after Churchill
gauging station by the Lahontan Reservoir, which was constructed in 1915 as part of the
Newlands Irrigation Project. This reservoir virtually cut off the Hg flow to the area
downstream.

Many large mills were developed in the Carson River Drainage Basin and the extraction of
precious metals was accomplished by an amalgamation process in which elemental Hg was
used to concentrate gold and silver from crushed ores (Bonzongo et al. 1996).
Figure 1.1: Location of the various hydrogeographic areas within the Carson River Drainage Basin. (Source: USGS Open File Report 93-356 pg. 3)
improvements to the original process which tended to hasten the separation process and improve gold recoveries. Hg recovery was not an important aspect of the refining process and the mills did not have any recovery streams. Prior to 1866, little effort was made to contain tailings, hence they were often discharged to receiving waters where they were carried downstream. After 1866, it became common to save tailings for reworking. The expected recovery of gold, silver and Hg from reworking was not known. The quantity of Hg that has been lost is difficult to estimate, and it is even more difficult to estimate how much might have entered the Carson River drainage system. Smith (1943) estimates that as much as about 7500 t of Hg has been lost to the environment.

Hg concentrations in the Lahontan Reservoir water range from 200 to 2100 ng/L (Cooper et al. 1985). Mostly Hg is associated with particles. As the river enters the reservoir, the water velocity drops, and the Hg-rich suspended sediment settles out. Bottom sediment samples range from 1.345 to 30.5 mg/kg with a mean concentration of 10 mg/kg (Cooper et al. 1985). The lowest concentrations occur in ‘the narrows’ or interconnecting channels and the highest concentrations are detected in the deep middle portions of the reservoir (Miller et al. 1995).

Hg has been reported in a wide variety of fish species from the Lahontan Reservoir by Cooper et al. (1983), Cooper et al. (1985), and Richins and Risser (1975). Concentrations of Hg exceeding 1.0 mg/kg were found in virtually all species of fish from the reservoir. This widespread occurrence of fish with Hg concentrations above the US Food and Drug Administration limit for human consumption of fish has prompted the Nevada Health Department to post fish consumption advisories around the lake. Even after a century, the Hg released during the mining activities continues to remain a cause of concern.

1.3 Modeling Approach and Objectives

This thesis details the development and application of a multispecies mass balance model to explain Hg dynamics in the Lahontan Reservoir. This work combines data
collected by USEPA for the reservoir and the background information from published sources, into a common framework. The framework, a QWASI equivalence multispecies model, is a mass balance model that quantifies Hg transport and transformation processes in the reservoir and helps us to understand the relative importance of sources and the dominant processes controlling its fate. With this understanding, more informed decisions can be made regarding the need for further investigations, which abatement measures would be effective, and the results that can be achieved through the implementation of these measures.

The model of Hg fate and transport and species interconversion in the Lahontan Reservoir is an extension of the QWASI (Quantitative Water Air Sediment Interaction) model of Mackay 1991, using the multi-species approach (Diamond et al. 1992). The key to modeling a speciating chemical like Hg lies in the assumption that concentration fractions of each species in each phase are at steady state. This makes the model simple to use and removes complications associated with obtaining species interconversion/ reaction rates. The steady-state model has been applied to generate three scenarios coincident with sampling events in the Lahontan Reservoir. These snapshots have been combined into an unsteady-state model. The model results are interpreted and a sensitivity analysis carried out to understand the effects of reservoir characteristics and parameter uncertainty. Long-term predictions are also discussed.

The main objectives of this modeling effort are:

- to understand the fate of Hg in the reservoir;
- to determine the dominant processes controlling Hg fate;
- to understand reservoir limnological characteristics that control Hg behaviour;
- make long term predictions on the fate of Hg;
- make suggestions and recommendations for future work for improved investigations of remedial options.
Considerable research effort has been devoted to understanding and quantifying mercury dynamics in aquatic systems. The efforts have been directed towards understanding aquatic transport and atmospheric deposition to remote water bodies, point sources of Hg and their impacts, biogeochemistry of Hg, and its speciation and interconversion characteristics, among others.

The review begins with a discussion of Hg, its properties and toxicity. Secondly, it focuses on MeHg and sources of methylation, third, a comparison of Hg in remote and polluted systems is carried out. Fourth, the effects of point and non-point sources of Hg and finally, an assessment of the pollutants and the characteristics of the aquatic systems contributing to bioaccumulation and bio-magnification of MeHg in biota are carried out.

2.1 Hg, its properties and toxicity

Hg is the third member of the Group IIB of the periodic table and exists in three oxidation states; the elemental state, which is liquid under normal pressure and temperature (Hg°), as mercurous ion Hg(I) (Hg\textsuperscript{2+}), and as mercuric ion Hg(II) (Hg\textsuperscript{2+}). Hg (I) and Hg (II) form a variety of compounds, although compounds from Hg(II) tend to be more stable. Hg(II) also forms a class of organometallic compounds of the type RHgX or RHgR', where R and R' are organic groups and X could be anions. Common compounds of this kind are monomethyl mercury (CH\textsubscript{3}Hg\textsuperscript{+}) and dimethyl mercury [(CH\textsubscript{3})\textsubscript{2}Hg]. Hg tends to exhibit significantly different behaviour from the triad it belong to, e.g., from zinc and cadmium. Hg is an enzyme and protein inhibitor whereas zinc plays an active role in protein, lipid, and carbohydrate metabolism (Cotton & Wilkinson 1980).

Human exposure is mainly to Hg° and MeHg, with the former present in the ambient atmosphere and the latter being present in fish and tissues of marine mammals (Clarkson 1994). The Minamata incident in Japan (Smith and Smith, 1975) and such other incidents have confirmed the health hazards associated with Hg ingestion. Hg, acting as an enzyme
There have been several large-scale poisonings in populations exposed to food contaminated with MeHg: e.g. Japan -Minamata (Smith and Smith, 1975) and Guatemala (Eyl 1971). In almost all the cases, the Hg usage was not as MeHg but as inorganic Hg salts. However, in most of these cases, MeHg had bioaccumulated and bioconcentrated within the fish that led to the poisonings upon consumption. Jensen and Jernelöv (1969) first reported the conversion of inorganic Hg to MeHg: mercuric chloride was partially converted to MeHg by aquarium sediments. Considerable research has and is still underway to determine the threshold value for body burden of MeHg in humans and a threshold for Hg concentration in fish meat for safe consumption. Toxicity of Hg to aquatic plants and biota, fish, and humans is discussed below.

**Toxicity to aquatic plants and biota:** All mercurial compounds are toxic to aquatic plants. Growth inhibition may occur by mercuric chloride at concentrations of 0.002 to 0.25 mg/L. Under most conditions, organic mercurials are significantly more toxic than inorganic forms. Hg has been reported to be more toxic than acids (Moore and Ramamoorthy 1984). However, toxicity to plants is nor reported to be common.

**Toxicity to fish** : Organic mercury compounds are significantly more toxic than inorganic forms. Temperature and dissolved oxygen affect the toxicity of mercury compounds in fish. High temperatures and low DO levels in some waters may significantly contribute to fish mortality. Further, the egg stage of fish is most susceptible to intoxication (Moore and Ramamoorthy 1984). Daoust (1981) has reported acute poisonings to rainbow trout, however, fish poisoning is not very widely reported.

**Toxicity in humans** : Organic mercurials induce toxicity which is known as Minamata disease. Clinical signs of intoxication include ataxia, depressed peripheral sensation, and gait and limb dysfunction. Sorbed MeHg is transported by the blood stream, and
MeHg is generally less than 70 days (National Research Council of Canada 1979).

### 2.2 MeHg and Methylation

The sources of MeHg to aquatic systems has been a concern for researchers for a long time. Sources of MeHg in aquatic systems have been identified to be made up of:

- internal (in lake) production (Rudd 1995)
- terrestrial runoff (Rudd et al. 1992; St. Louis et al. 1994) and
- atmospheric deposition (Hultberg et al. 1994)

For contaminated reservoirs, internal production of MeHg is the most important source (Rudd et al. 1995). The biogeochemical cycle of Hg is illustrated in Figure 2.1, which indicates that Hg is capable of interconverting from any form to MeHg, directly or indirectly. The cycle indicates that dimethyl mercury (DMHg), MeHg, Hg(II) and gaseous elemental Hg (Hg") may interconvert in the atmosphere, aquatic and sedimentary environments. Some generalization that emerge are (Craig 1986):

- Hg is potentially exchangeable among the air, land, and water phases;
- Hg is potentially capable of being converted to and taken up by biota as MeHg form;
- in an aquatic system, MeHg can be formed directly from HgII under anaerobic conditions, mediated by humic substances and / or bacteria;
- MeHg and DMHg can be formed indirectly from either Hg(II) or Hg" in the presence of oxygen or under oxidizing conditions;
- pH affects methylation, with acidic pH promoting MeHg formation and alkaline pH promoting demethylation and volatilization (Hudson et al. 1994).

More information is required to discuss the numerous interconversion processes, however, the overall equilibrium in nature is towards methylation, as MeHg and DMHg are not tightly bound to substrates, are water soluble or volatile, and are rapidly assimilated by biota.
Figure 2.1: The biogeochemical cycle for mercury. (source: Craig 1986)
Factors affecting methylation include:

- redox conditions and sulfur cycling. Dissolved oxygen is a key factor with methylation greatest in the anoxic zone of water column (Watras et al 1994; Porcella 1994).
- presence of chlorophyll α, sulfate, chloride, nitrate and calcium influence MeHg concentrations (Watras et al. 1994). Methylation is linked to sulfur cycling, perhaps via sulfate reduction (Compreau and Bartha, 1985, Gilmour and Henry, 1991).
- presence of high detrital particles reduce production of MeHg as they compete for Hg(II) (Rudd 1995)

The type of Hg and its chemistry are important for methylation as total Hg(II) serves as the substrate for methylation (Hudson et al. 1994). However, the bioavailability of Hg(II) depends on the type of Hg in the system. Lechler et al. (1994) reported that even with high Hg concentrations, most Hg in Lahontan Reservoir was unavailable due to its presence as an amalgam or as sulfide. Kelly et al. (1995) have argued that there is no relation between total Hg and MeHg concentrations in aquatic systems unless the data set includes seepage lakes (with no runoff or streams) and where lakes excludes those with anoxic hypolimnia. These are some of the factors affecting methylation.

2.3 Mercury in Lakes and Reservoirs

Hg has been studied extensively in many aquatic systems, in North America, Europe and Asia. It is a metal of concern in both remote water bodies, as well as, in aquatic systems receiving Hg bearing pollutants. High levels of Hg in fish have been observed in remote lakes in Wisconsin (Bloom and Watras 1989), Ontario (Rudd and
Remote lakes receive Hg through atmospheric transport and deposition (Hurley et al. 1991; Sorensen et al. 1990). The elevated levels of Hg in rivers and reservoirs in Brazil (Malm et al. 1990; Aula et al. 1994) affected by Hg pollution due to mining, in the Lahontan Reservoir (Bonzongo et al. 1996) polluted due to mining wastes, or in Onondaga Lake in New York (Bloom and Efler 1990) and the English-Wabigoon River in Canada (Parks et al. 1986), that were recipients of chlor-alkali plant effluents and geologic sources (Rasmussen 1994), are the result of point sources of Hg pollution. In Table 2.1, total Hg and MeHg concentrations from various studies, in remote and polluted aquatic systems, are summarized.

The comparison reveals differences in Hg and MeHg concentrations in remote and polluted water bodies. Total Hg concentrations in polluted systems vary from 0.04 to 2107 ng/L whereas the variation in remote systems is from 0.14 to 6.8 ng/L. MeHg concentrations in remote lakes vary between 0.002 to 1.22 ng/L compared to polluted lakes where the variation is 0.04 to 7.2. Onondaga Lake, a polluted lake, has 10% MeHg concentrations for an input of 10,000 kgs (Bloom and Efler 1989) compared to Lahontan Reservoir MeHg of 0.3% for over 4000 kg/yr of Hg loading for over 100 years (EPA 1996; Cooper et al. 1985). Similarly, the English-Wabigoon River system has MeHg of 3.5% for an input of 75,000 of Hg over 10 years (Parks et al. 1989). Loadings to remote systems are at least one order of magnitude lower (Petersen et al. 1995; Sorensen et al. 1990) than the polluted systems. Thus, it appears as if the type of Hg and the characteristics of the aquatic system control Hg dynamics. The question that emerges is why there is this difference in percent MeHg even when the loadings are high and what limits conversion into MeHg?

Veita (1984) reports that in “a typical freshwater lake”, more than 90% of Hg that can be methylated and can enter the food chain, is present in the top 5 cm of the sediments and
Table 2.1: Comparison of Hg concentrations in polluted and remote lakes/reservoirs.

<table>
<thead>
<tr>
<th>System</th>
<th>Location</th>
<th>Hg&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>MeHg</th>
<th>% MeHg</th>
<th>Pollution source</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lahontan Reservoir</td>
<td>Nevada</td>
<td>4 - 2107</td>
<td>0.3</td>
<td>0.3</td>
<td>Mining</td>
<td>Bonzongo et al. (1996)</td>
</tr>
<tr>
<td>English-Wabigoon River</td>
<td>Ontario</td>
<td>5 - 80</td>
<td>1.8</td>
<td>3.5</td>
<td>Chlor-alkali</td>
<td>Furutani and Rudd (1980)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Parks et al. (1989)</td>
</tr>
<tr>
<td>Onondaga Lake</td>
<td>New York</td>
<td>7 - 19</td>
<td>0.4</td>
<td>10</td>
<td>Chlor-alkali</td>
<td>Bloom and Effler (1990)</td>
</tr>
<tr>
<td>Lake Union</td>
<td>Washington</td>
<td>1.7</td>
<td>0.04</td>
<td>2.3</td>
<td>Urban</td>
<td>Bloom (1989)</td>
</tr>
<tr>
<td>Madeira River</td>
<td>Brazil</td>
<td>0.04 - 10</td>
<td>n.a</td>
<td>-</td>
<td>Mining</td>
<td>Malm et al. (1990)</td>
</tr>
<tr>
<td>5 Seepage Lakes</td>
<td>Wisconsin</td>
<td>0.5 - 2.2</td>
<td>0.04</td>
<td>6.8</td>
<td>Atm dep</td>
<td>Bloom and Watras (1989)</td>
</tr>
<tr>
<td>4 Drainage Lakes</td>
<td>Sweden</td>
<td>1.2 - 2.5</td>
<td>0.08</td>
<td>9.6</td>
<td>Atm dep</td>
<td>Lee (1987)</td>
</tr>
<tr>
<td>Allequash Creek</td>
<td>Wisconsin</td>
<td>0.9 - 6.8</td>
<td>0.02</td>
<td>18</td>
<td>Atm dep</td>
<td>Krabbenhoft et al. (1995)</td>
</tr>
<tr>
<td>Lake Baikal</td>
<td>Russia</td>
<td>0.14 - 0.77</td>
<td>0.002</td>
<td>5</td>
<td>Atm dep</td>
<td>Meuleman et al. (1995)</td>
</tr>
</tbody>
</table>
only about 1% is within the fish. The proportions of MeHg in contrast, would be 49% in sediments and 48% in fish. Thus, the investigation must focus on the net rates of methylation and factors influencing the content of MeHg in biota.

2.4 Point and Non-point Sources of Hg

In the section above, I presented the concentrations of Hg and MeHg in remote and polluted aquatic systems. Based on above discussions on Hg biogeochemistry, MeHg interconversions, Hg properties and its toxicity, this section deals with the difference in Hg behaviour in the two systems. Several hypothesis have been proposed to account for high rates of methylation. Mason and Fitzgerald (1990) proposed that the Hg(II) fraction is the substrate for methylation and Hg⁰ formation in natural waters, and that the reactive Hg(II) determination provided a suitable measure of this fraction. Some other hypotheses include increased lake acidification (Winfrey and Rudd 1990); and favourable redox conditions and sulfur recycling (Gilmour and Henry 1991).

Significant research has focused on understanding Hg dynamics in remote lakes. Hurley et al. (1994a) studied Hg dynamics in seepage Wisconsin lakes and found that particulate transport of Hg in the water column was primarily responsible for Hg dynamics within the lakes. MeHg content of particles responded to lake limnology and seasons with MeHg being highest during summer stratification. Parkman et al. (1994) studied the methylation of a permanently stratified Norwegian fiord and found that net methylation is favored in anoxic environments and appeared to be an extracellular process, enhanced by bacteria. Watras et al. (1994) reported, after studying seven lakes in Wisconsin receiving Hg only through atmospheric deposition, that in-situ production of MeHg was an important source and the production of MeHg was highest at the sediment-water interface. The important message from remote lake studies has been that input form of Hg is predominantly oxidised HgII and this HgII being available for conversion, is converted by microbes under favorable circumstances, to MeHg (Fitzgerald et al. 1991; Porcella 1994).
industrial discharges primarily as inorganic Hg(II) (Parks et al. 1986; Bloom and Effler 1990). The response of the polluted systems to these point sources of Hg is dissimilar to the remote lakes. Onondaga Lake, New York, which has been receiving industrial effluent, has high concentrations of total Hg, Hg(II) and MeHg, influenced by limnological conditions. In Onondaga lake, Hg(II) conversion to MeHg is believed to be occurring due to low oxygen levels and presence of sulfides in the hypolimnion (Bloom and Effler 1990).

In the English-Wabigoon River system, MeHg levels in fish have continued to remain seriously elevated as a result of the discharge of 10,000 kg of inorganic Hg between 1962 to 1970 (Parks and Hamilton 1987). It was observed that MeHg and Hg(II) in the Wabigoon River water are predominantly in particulate form during spring flood, while dissolved forms increase during summer due to microbial activity (Jackson et al. 1982). It was further found that Hg bound to wood-chip deposits was less readily methylated than the Hg bound to silt-clay mud. Hg species in particulates were associated with sulfides, Fe, Mn and these associations varied with season and Hg species (Jackson et al. 1982). Thus, in systems that have received Hg point-source loadings, the availability of Hg(II) is probably the limiting factor controlling MeHg concentrations (Lechler et al. 1994; Mason and Fitzgerald 1990).

In Lahontan Reservoir, Nevada about 6,500,000 kg of Hg was released into the environment during the latter part of 19th century and the reservoir still, after nearly nine decades, has elevated MeHg levels in the fish (Bonzongo et al. 1996). The type of Hg in the Lahontan Reservoir system differs from the other polluted system inputs as most of the Hg is particle-bound. Further, Hg occurs as a tightly bound amalgam or sulfide that is unavailable for interconversion (Lechler et al. 1994).

The mode of Hg discharge, the type of Hg, and seasonal variability in Hg transport processes all introduce variability in the exposure experienced by biotic populations. Hence, systems require characterization of temporal and spatial variability for thorough
understanding of Hg behaviour. It is believed that aquatic systems will respond better to remedial measures implemented to point sources of Hg after understanding Hg dynamics.
3. QWASI Multi-Species Model

The QWASI multi-species model applied to the Lahontan Reservoir is based on the fugacity approach developed by Mackay and co-workers (e.g., Mackay 1991) with modifications by Diamond and Mackay (e.g., Diamond et al. 1992) to accommodate non-volatile chemicals and those that exist as multiple interconverting species. The important aspects of this model relevant to the work carried out are discussed in this section.

3.1 Fugacity and Equivalence Concepts

Mackay and Paterson (1981, 1982), Paterson and Mackay (1985), and Mackay (1991) have discussed the concept of fugacity in environmental modeling. In terms of the principle of phase equilibrium thermodynamics, when a solute achieves equilibrium between phases, such as air and water, water and sediment, it has an equal chemical potential in both phases. Chemical will diffuse from phases of high to low chemical potential. Thus, chemical potential is used as a criterion of equilibrium. Due to difficulty in expressing chemical potential and concentration linearly, equilibrium is defined using “fugacity”. Fugacity has the units of pressure and denotes the fleeing or escaping tendency of the chemical from one phase to another. Equilibrium is attained between two phases when the fugacity in Phase I (escaping tendency of the chemical from PhaseI to Phase II) is exactly balanced by the fugacity in the Phase II. It is identical to partial pressure in ideal gases (Mackay, 1991).

For each chemical and each medium, the linear relationship between fugacity and concentration is given as $C = Z \times f$, where $C$ denotes concentration (mol/m³), $Z$ is the “fugacity capacity” with units of mol/m³.Pa and $f$ denotes fugacity (Pa). Each chemical has a unique value of $Z$ for each phase at a defined temperature. Phases of high $Z$ (e.g., sediments and fish) are able to absorb a much greater quantity of material, with a minimal increase in fugacity. It follows that the pollutants tend to partition into these high $Z$ phases and achieve elevated concentrations. Conversely, phases of low $Z$ values will tend to
Z values can be estimated from partition coefficients. The use of fugacity as a surrogate for concentration in environmental modeling is very convenient for organic chemicals with measurable vapor pressures, but it is inconvenient for chemicals with low or negligible vapor pressures. In case of chemicals with negligible or unknown vapor pressure like metals and polymers, an equilibrium criterion analogous to fugacity, termed “aqueous equivalent concentration” or *aquivalence*, having units of mol/m³ is used. Estimation of Z values in the fugacity approach starts in the air phase (subscript A) with all species of $Z_A$ values being $1/RT$. With equivalence, Z values are redefined, with Z value for water is defined as 1.00 and the subsequent Z values are determined from partition coefficients. The new Z is dimensionless (Mackay and Diamond, 1989).

### 3.2 Application of the model to Speciating Chemicals

Diamond et al. (1992) extended the equivalence model application to treat the multi-phase distribution of chemicals present as several, interconverting species. The model, in this thesis, has been adapted from Diamond et al. (1992) to consider the behaviour of mercury and its species in a multi-phase system, under steady-state and unsteady-state conditions. The QWASI fugacity/ equivalence approach has been applied to the mercury and its forms in the Lahontan Reservoir to consolidate the multi-species mass balance expressions into pseudo single-component expressions and exploit the existing experience with mass balance modeling of such chemicals in air-water-sediment systems.

As discussed previously, fugacity $f$ (Pa) or equivalence $Q$ (mol/m³) and concentration $C$ (mol/m³) are related through the proportionality constant $Z$ (mol/m³.Pa) and Z respectively. For multiple species, the concentration in phase i of species j, $C_{ij}$, is equal to the product of $Q_{ij}$ and $Z_{ij}$ (Diamond et al., 1992).
Similarly, we calculate equivalence fractions $Y_{ij}$ as $Q_{ij}/Q_{1j}$ with $\sum Y_{ij}$ also equaling 1.0. The relationship between $X_{ij}$ and $Y_{ij}$ is:

$$Y_{\Lambda j} = \frac{(X_{\Lambda j}/Z_{\Lambda j})}{\sum (X_{\Lambda i}/Z_{\Lambda i})}; \text{ and } Z_{\Lambda i} = \sum Y_{\Lambda j} Z_{\Lambda j}$$

3.1

Under physical equilibrium conditions, the total equivalence $Q_{ij}$ of the chemical in all phases will be equal and the equivalences of each chemical species in all phases will be equal. However, when the model is applied to a system where the chemicals are not at equilibrium, which is usually the case, then the equivalence values will normally not be equal.

### 3.3 $D$ Values

In the natural environment, chemicals react and move by advection. Local contamination can result from discharge of chemical from upstream regions or other direct sources. Chemicals move between phases by means of diffusive processes. In a multi-species system, species interconversion can play an important role in material movement. It is our task to quantify the various transport and transformation processes.

$D$ Values (mol/h - transport or transformation parameter) have been defined by Diamond et al. (1992) to quantify these processes. Except for emissions being defined directly, process rates $N$ (mol/h), are expressed as the product of equivalence $Q$ and $D$ value, e.g., $N = Q*D$. Species specific $D$ values for a multi-species system can be calculated as:

- $GZ_{ij}$ where $G$ (m$^3$/h) refers to the bulk material movement.
- $k_jAZ_{ij}$ where $k_j$ (m/h) is a mass transfer coefficient and $A$ (m$^2$) is area.
- $B_jA/LZ_{ij}$ where $B$ is a diffusivity (m$^2$/h) and $L$ is path length (m).

The $D$ values considered in the model are listed in Table 3.1.
Table 3.1: Process and rate expressions used in the Lahontan Reservoir model

<table>
<thead>
<tr>
<th>Processes</th>
<th>D Values (m³/h)</th>
<th>Rates (mol/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water inflow</td>
<td>DIT = GI*ZW</td>
<td>DIT*QW</td>
</tr>
<tr>
<td>Water outflow</td>
<td>DJT = GJ*ZW</td>
<td>DJT*QW</td>
</tr>
<tr>
<td>Particle inflow</td>
<td>DXT = GX*ZP</td>
<td>DXT*QW</td>
</tr>
<tr>
<td>Particle outflow</td>
<td>DYT = GY*ZP</td>
<td>DYT*QW</td>
</tr>
<tr>
<td>Truckee Inflow</td>
<td>DIT = GT*ZT</td>
<td>DIT*QTR</td>
</tr>
<tr>
<td>Rain dissolution</td>
<td>DMT = GM*ZW</td>
<td>DMT*QA</td>
</tr>
<tr>
<td>Wet deposition</td>
<td>DCT = GC*ZQ</td>
<td>DCT*QA</td>
</tr>
<tr>
<td>Dry deposition</td>
<td>DQT = GQ*ZQ</td>
<td>DQT*QA</td>
</tr>
<tr>
<td>Volatilization</td>
<td>DVT = 1/[(1/(KV<em>AW</em>ZW)) + 1/(KA<em>AW</em>ZW)]</td>
<td>DVT*QW</td>
</tr>
<tr>
<td>Absorption</td>
<td>DAT = 1/[(1/(KV<em>AW</em>ZW)) + 1/(KA<em>AW</em>ZW)]</td>
<td>DAT*QA</td>
</tr>
<tr>
<td>SedU deposition</td>
<td>DDT = GD*ZP</td>
<td>DDT*QW</td>
</tr>
<tr>
<td>SedU resuspension</td>
<td>DRT = GR*ZSU</td>
<td>DRT*QSU</td>
</tr>
<tr>
<td>SedU burial</td>
<td>DBUT = GB*ZSU</td>
<td>DBUT*QSU</td>
</tr>
<tr>
<td>SedL burial</td>
<td>DBLT = GB*ZSL</td>
<td>DBLT*QSL</td>
</tr>
<tr>
<td>SedU-SedL diffusion</td>
<td>DSUT = KS<em>AS</em>ZW</td>
<td>DSUT*QSU</td>
</tr>
<tr>
<td>SedL-SedU diffusion</td>
<td>DSLT = KS<em>AS</em>ZW</td>
<td>DSLT*QSU</td>
</tr>
<tr>
<td>SedU-SedL mixing</td>
<td>DMUT = KM<em>AS</em>ZSU</td>
<td>DMUT*QSU</td>
</tr>
<tr>
<td>SedL-SedU mixing</td>
<td>DMLT = KM<em>AS</em>ZSL</td>
<td>DMLT*QSL</td>
</tr>
<tr>
<td>Wat-SedU diffusion</td>
<td>DWST = KT<em>AW</em>ZW</td>
<td>DWST*QW</td>
</tr>
<tr>
<td>SedU-Wat diffusion</td>
<td>DSWT = KT<em>AS</em>ZW</td>
<td>DSWT*QSU</td>
</tr>
<tr>
<td>SedL_Backmix</td>
<td>DSBT = GCU*AS</td>
<td>DSBT*QSL</td>
</tr>
</tbody>
</table>

- The rate is the product of D (m³/h) and equivalence Q (mol/ m³).
- G values are flows (m³/h) of a phase. Z values are equivalence capacities (dimensionless).
3.4 The QWASI Model

The environment can be viewed as consisting of a number of compartments or phases viz. air, water, sediment, soils, biota etc., which are in contact, and between which chemicals migrate through diffusive and non-diffusive processes. In developing a model, one must keep it simple and yet, not neglect important characteristics. This delicate balance between simplicity and clarity of the model vis-à-vis the inclusion of heterogeneity of the system leads us to choose the QWASI model developed by Mackay (1991).

The simplest view of the environment is that of a small number of phases, each of which is homogeneous or well-mixed. The model treats the three primary, well mixed compartments within each of which equilibrium is assumed to apply - air (consisting of air, rain water and aerosol), water (consisting of water and particulate matter), and sediment (consisting of particulate matter and pore-water). A chemical enters the water column by direct emissions, via inflow of particles and water, and from air by absorption, deposition (wet and dry) and precipitation. The chemical is transferred out of the system by the outflow of water and suspended particles. Chemical movement between water and sediment takes place through diffusion, deposition, resuspension and chemical may leave the system through sediment burial to inaccessible depths. The chemical also may be lost by volatilization to air, through bio-degradation, and abiotic reactions. The chemical may also be interconverting among its various species, mediated by the conditions in various phases. A mass balance can be written for each compartment using the D values and equivalences of the compartments. These equations are solved to get the equivalence of each compartment, that is then used to calculate the specific transformation or transport rates. Figure 3.1 illustrates the QWASI model transport and transformation terms used in the Lahontan model.
Figure 3.1: Illustration of compartments and processes considered in the QWASI model for mercury behavior in one basin of the Lahontan Reservoir.
4. Lahontan Reservoir Description, Steady-State Model Parameterization and Calibration

4.1 Lahontan Reservoir Description

Lahontan Reservoir is located in west central Nevada approximately 72 km southeast of Reno, 39° 27' 45" N, 119° 04' 00" W. Figure 4.1 shows the location of the reservoir. The reservoir receives most of its water from the Carson River to the south basin, and secondarily from Truckee Canal into north basin. The Lahontan dam, at the north end of the reservoir, is an earth and gravelfill structure constructed by US Bureau of Reclamation and completed in June 1915. The reservoir is part of the Newland’s Irrigation Project and stores water derived from the Carson River and a trans-basin diversion from the Truckee River. The water is used during the growing season to irrigate agricultural lands in the Lahontan Valley, in addition to supplying a small amount of hydroelectric power (Cooper et al., 1983).

Lahontan Reservoir has a surface area of 4.41E07 m² with a shoreline of 104 km when full (Katzer 1972). It has a maximum length of slightly over 27 km and a maximum width of 3.9 km. The storage volume when at capacity was estimated to be 3.57E08 m³ in 1972 (Katzer 1972). The maximum depth of the reservoir is found in the north basin (near the dam) at 26 m and a mean depth (volume/ surface area) of the reservoir is 8.1 m (Cooper et al., 1983).

The average annual flow of the Carson River is estimated at 3.354E08 m³ (Glancy and Katzer, 1976) and flow from the Truckee Canal, measured near Hazen, is 1.776E08 m³ or about 40% of the annual input (Garcia et al., 1992). The average annual flow of the Carson River below Lahontan Dam is 4.661E08 m³ (Glancy and Katzer, 1976).

Construction of the Lahontan Dam has changed the ground-water flow in the surrounding area. As the reservoir filled, water seeped into the subsurface, causing a rise in the water table. Measurements in the vicinity of the dam indicated that the water table was within a few meters of the Reservoir’s surface. The high water table indicates that reservoir water
Figure 4.1: Location of the Lahontan Reservoir in Western United States
recharged the local ground water system (Dastoor, 1992). However, ground water discharge at the western edge of the Dayton Valley hydrogeographic area has been estimated at 1.97E05 m³/year (USGS Open File Report 93-356), less than 1% of the average annual inflow to the reservoir. Therefore, ground-water recharge or discharge can be assumed to be negligible for the purposes of the model.

This modeling effort is an integral part of the Carson River Mercury Site remedial investigation by US Environmental Protection Agency (EPA). To understand particle and Hg dynamics, EPA conducted three (3) sampling events in September 1994, February 1995, and May 1995 in the reservoir. The plan was to collect surface water and sediments from a near-shore and mid-basin sites in each basin, and surface water from the interconnecting channels. Unfortunately, due to the drought in 1994 and the variability of the system, there were deviations in the plan. These deviations are discussed in brief to highlight the variability of the system.

September 1994: All inter-connecting channels were dry. Mid-basin samples could not be collected from south or middle basins. Only shallow (<1 meter) water was standing in these two basins and these samples were designated near-shore samples. In north basin, samples from near-shore and mid-basin sites were collected.

February 1995: Inter-connecting channels had minimal flows and samples could be collected. In both north and middle basins, samples from near-shore and mid-basin sites were collected. In south basin, conditions continued to be similar to Sept. 1994 and only near-shore samples were collected.

May 1995: The reservoir was full due to high flow conditions typical of a once in 50 year event. All the samples were taken as planned.

Water samples were analysed for total suspended solids, total Hg (unfiltered) and total dissolved Hg (<0.2 μm) and its species. Total Hg and species were determined by methods described by Bloom (1989), with modifications described by Liang et al. (1994) and Watras et al. (1995). The three sampling trip data were compiled and validated. This data forms the basis for this modelling effort and is referred to as EPA 1996 in this thesis.
4.2 Parameterization of steady-state model

The Lahontan Reservoir is complex owing to a high degree of spatial variability coupled with temporal variability in flow and stages. Such variability is caused by natural system fluctuation and reservoir operations that support downstream agricultural activities (Warwick and Heim, 1995).

4.2.1 Reservoir Water and Sediment Volumes

The Lahontan Reservoir consists of three distinct basins with water from the Carson River entering the south basin, and flowing to the middle and finally the north basin, where the Lahontan Dam is located. Narrow channels connect the three basins and there is a sizable delta at the mouth of the river. Figure 4.2 depicts the segmentation. The interconnecting channels were incorporated equally into adjacent basins. The basins are assumed to be well-mixed (Cooper et al. 1983).

The average reservoir volume varies from 1.12E8 m³ in September to 3.08E8 m³ in May (Personal communication, Willis Hyde, Watermaster, Truckee Carson Irrigation Department) (Figure 4.3). During low flows, the south basin can dry almost entirely. The north basin volume varies the least. Unfortunately, basin volumes and their temporal variations are not available and have been estimated. Basin areas under full conditions were obtained by digital estimates of surface areas calculated from United States Geological Survey (USGS) topographic maps (39119-C1-TM-024, 39119-C2-TM-024, 39119-D1-TM-024, AND 39119-D2-TM-024). Based on the volume of reservoir (data obtained from Truckee Carson Irrigation Department) for the times when the samples were drawn, the volumes and areas were apportioned to the three basins based on bathymetric estimates of depth obtained from Katzer (1972). Estimates of water surface area and volume are sensitive to hydrologic conditions that vary widely within and
Figure 4.2: The Lahontan Reservoir
Figure 4.3: Reservoir monthly average volumes.
(Source: W. Hyde, TCID Watermaster, personal communication)
Sediments underlying the water columns are assumed to consist of two vertical layers underneath which is buried sediments (Figure 3.1). Near-shore sediments are typically sandy with low mercury concentrations, whereas mid-basin sediments are fine-grained with much higher mercury concentrations (EPA 1996; Miller et al. 1995). I have considered only the central sediment areas for modeling purposes. In some cases, I have used near-shore data when mid-basin data were unavailable. Active sediment areas were judged as 80, 65 and 60% of the surface water areas of the south, middle and north basins, respectively, based on basin bathymetry.

Sediments in all basins are assumed to have same porosity of 90 and 60% for the upper and lower sediment layers, respectively. This is an assumption based on data from other similar systems.

### 4.2.2 Reservoir Flows

The Lahontan Reservoir is characterized by enormous fluctuations in discharges from the Carson River and subsequent variations in basin volumes within a year and year-to-year. Carson River water passes through the three basins sequentially from south to north. Backflow and subsequent mixing created due to flow of Truckee canal water into the north basin maybe significant, as suggested by Miller et al. (1995). Backmixing from north to middle basin has been assumed to be 20% of the input Truckee flow. No backmixing has been considered from middle to south basin.

Over the past 50 years, discharge rates have varied from 0 to as high as 9.5E06 m³/day. with average discharge being 2.06E06 ± 2.50E06 (Figure 4.4). The flow rates during the study period were twice as high as the long term average (Figure 4.5). The data for Carson River and Truckee Canal flows are obtained from USGS measurements.
Figure 4.4: Carson River flow during July 1994 to June 1995.

Figure 4.5: Mean monthly flow and quartile statistics, Carson River gauge near Fort Churchill, USGS station 10312000, water years 1919-69. Modified from Glancy and Katzer (1976)
Characterization of suspended particles and sediments is critical to the model of the Lahontan Reservoir since most of the mercury is strongly bound (>90%) to particles (EPA 1996). Particle inputs to the Reservoir come from the Carson River, Truckee Canal, and mixing and movement of buried sediments. The reservoir bed sediments are the historical repository of mercury and show wide fluctuations in concentration from 20 ng/g to 99400 ng/g (Heim 1996).

There is insufficient data on rates of particle movement, such as annual sediment accumulation or burial, inflow particle concentrations and bank erosion to construct a complete picture of particle dynamics. Miller et al. (1995) have suggested that shrink and swell processes, the result of periodic sediment drying and wetting, result in sediment layers mixing vertically. They postulate this mechanism to account for disturbed depth profiles of mercury, lead and cesium. If sediment mixing occurs, then heavily contaminated sediments at depth can be reworked towards upper sediment depths. This, in effect, can act as a source of mercury from deep contaminated sediments.

Two sediment layers are considered in each basin, namely an upper layer (U) that is in communication with water and a lower layer (L) that receives sediments from U, as well as, the deep buried sediments that may act as source of Hg (Figure 4.6). The incoming particles deposit within the upper sediment layer of the basins. The particles are resuspended and also lost to the lower sediment layer as sediment burial. The communication between upper and lower sediment layers is through physical mixing and finally, there is net burial out of the system. It is hypothesized that Hg inputs from buried sediments should decline as the Hg concentration in the buried sediments is diluted by mixing with less concentrated surface sediments.
Figure 4.6: Geologic map of Lahontan Reservoir and mercury concentrations within the geomorphological units (Source: Miller et al. 1995)
4.2.4 Suspended Particles and Particle Balance

The reservoir flows, basin levels and consequently, particle movement rates are extremely variable; this was clearly observed during the sampling trips. The input of particles varied from 528,000 kg/d during May (Fig. 4.7) to 44 kg/d during September (Fig. 4.8). The reservoir itself is highly turbid, with suspended particle concentrations ranging between 15 mg/L to 60 mg/L (EPA 1996).

During the 3 sampling events, as discussed in section 4.2.1, sediment traps were deployed in the three basins to generate data on sedimentation processes (Table 4.1). The data obtained gave order of magnitude values for gross deposition (deposition plus resuspension), depending on the position of the trap. Trap catches were used as a guide only because most traps were deployed close to the sediment-water interface and therefore contained depositing and resuspending material. As well, there are uncertainties inherent in use of traps for quantification purposes (e.g., Bloesch & Burns 1980).

A particle balance was constructed for the reservoir, that was constrained by measured concentrations of suspended particles entering the reservoir from the Carson River, particles leaving each basin, and trap catches (Figure 4.7 to 4.9). It was found that the particle balance could not be sustained without a 'clean particle' source. As mentioned earlier, the Truckee Canal contributes about 40% of annual water budget to the reservoir, however its contribution to the particle budget is unclear. Truckee Canal’s measurement during Feb 1995 indicated 106 mg/L of suspended particles with Hg concentration of 46 ng/L (EPA 1996), suggesting that the canal is a source for 'clean particles'. To satisfy particle balance, Truckee flow was considered into the north basin and backflow (20% of input) was assumed from north to middle basin to sustain the particle balance in the middle basin. EPA 1996 provided the information on Truckee Canal suspended particles and Hg concentrations. Truckee Canal flow data was obtained from USGS published figures. The particle balance indicated the following temporal trends:
### Table 4.1: Deposition rates calculated from sediment traps

(source: EPA 1996 trap data)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Dry fraction of mass collected</th>
<th>Collection duration (hr)</th>
<th>Computed sediment mass (mg)</th>
<th>Trap Depth (m)</th>
<th>Deposition Flux (g/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>0.00191</td>
<td>120.3</td>
<td>477.5</td>
<td>18.6</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>0.00262</td>
<td>120.3</td>
<td>655.0</td>
<td>18.6</td>
<td>28.7</td>
</tr>
<tr>
<td></td>
<td>0.00221</td>
<td>121.2</td>
<td>552.5</td>
<td>10.7</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>0.00278</td>
<td>121.2</td>
<td>695.0</td>
<td>10.7</td>
<td>30.2</td>
</tr>
<tr>
<td></td>
<td>0.00282</td>
<td>120.3</td>
<td>705.0</td>
<td>9.5</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>0.0025</td>
<td>120.3</td>
<td>625.0</td>
<td>9.5</td>
<td>27.3</td>
</tr>
<tr>
<td>Middle</td>
<td>0.00158</td>
<td>93.2</td>
<td>395.0</td>
<td>8.2</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>0.00164</td>
<td>93.2</td>
<td>410.0</td>
<td>8.2</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td>0.00187</td>
<td>121.8</td>
<td>467.5</td>
<td>5.8</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>0.00162</td>
<td>121.8</td>
<td>405.0</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>0.000173</td>
<td>29.5</td>
<td>43.3</td>
<td>2.7</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>0.000168</td>
<td>29.5</td>
<td>42.0</td>
<td></td>
<td>7.5</td>
</tr>
</tbody>
</table>

* A, B, D are measured.  
** C, E are calculated.

**Notes:**

1. C = A*1E06*sample vol(L) = mg sediment collected.
2. Area of trap = 4.56E-03 m²
3. E = C/B/Area of trap.
Figure 4.7: Particle Balance for the Reservoir for May 1995.
Values expressed in kg/d.
Figure 4.8: Particle Balance for the Reservoir during February, 1995.
Values expressed in kg/d.
Figure 4.9: Particle Balance for the Reservoir during September 1994.
Values expressed in kg/d.
May 95 (Fig 4.7): During May 95, the reservoir receives a high load of particles from the Carson River. Deposition rates, which are high, decrease from south to north basin. Resuspension rates also decline from south to north basin, attributable to high turbulence in the shallow south and middle basins.

February 95 (Fig 4.8): Particle inputs are greatest in north basin followed by south and middle basins, due to high inputs from the Truckee Canal (EPA 1996). Deposition and resuspension rates again decline from south to north, as in May. The resuspension rate is minimal in north basin due to high water depth and low turbulence.

September 94 (Fig 4.9): Rates of particle movement throughout the system are minimal due to low flow rates. Particle inputs are about 10000 times lower in Sept than May. Deposition and resuspension rates decrease from south to north as is the case for all sampling scenarios. Although the input particle amounts are low, relatively high rates of resuspension and deposition are required to sustain the suspended particle concentrations in the basins. The steady-state particle balance for the water column, upper and lower sediment layers of each basin can be written as, respectively:

\[
\text{Inflow (Carson River + Truckee Canal) + Resuspension} = \text{Outflow + Deposition} \quad 4.2.4.1
\]

\[
\text{Deposition} + (\text{Mixing } )_{1 \rightarrow 2} = \text{Resuspension} + \text{Burial}_{1} + (\text{Mixing } )_{1 \rightarrow 2} \quad 4.2.4.2
\]

\[
\text{Burial}_{1} + (\text{Mixing } )_{1 \rightarrow 2} + \text{Bur.Sed.In} = (\text{Mixing } )_{1 \rightarrow 2} + \text{Burial}_{1} \quad 4.2.4.3
\]

While the suggested parameterization of the particle balance are consistent with the qualitative observations and match computed parameter trends (Tables 4.2 to 4.4), the values are not necessarily unique, i.e., another combination of these parameter values may yield similar results. Thus, the particular parameter values contain considerable uncertainty.
Table 4.2: Reservoir parameters - May, 1995

<table>
<thead>
<tr>
<th>Source</th>
<th>South Basin</th>
<th>Middle Basin</th>
<th>North Basin</th>
<th>Reservoir Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Area (m²)</td>
<td>1.63E+07</td>
<td>1.19E+07</td>
<td>1.89E+07</td>
<td></td>
</tr>
<tr>
<td>Mean Depth (m)</td>
<td>5</td>
<td>7</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Water Volume (m³)</td>
<td>8.30E+07</td>
<td>8.30E+07</td>
<td>2.07E+08</td>
<td>Bathymetric map</td>
</tr>
<tr>
<td>Active Sediment Area (m²)</td>
<td>1.38E+07</td>
<td>7.70E+06</td>
<td>1.13E+07</td>
<td>by Katzer (1972)</td>
</tr>
<tr>
<td>Sediment U Depth (m)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sediment L Depth (m)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Densities (kg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Susp. Particle</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosols</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Rates (m³/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water-air Volatilization</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-water Absorption</td>
<td>0.01</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Sed.-water Diffusion</td>
<td>0.0002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sed.-sed. Diffusion</td>
<td>1.00E-08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc. Susp. Particle(mg/L)</td>
<td>22.8</td>
<td>21</td>
<td>21.4</td>
<td>EPA</td>
</tr>
<tr>
<td>Sed. U Porosity</td>
<td>0.1</td>
<td></td>
<td></td>
<td>assumed</td>
</tr>
<tr>
<td>Sed. L Porosity</td>
<td>0.4</td>
<td></td>
<td></td>
<td>assumed</td>
</tr>
<tr>
<td>Conc. Susp. Part. inflow(mg/L)</td>
<td>105.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc. Susp. Part. truckee(mg/L)</td>
<td>106.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Flows (m³/y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflow</td>
<td>1.82E+09</td>
<td>1.82E+09</td>
<td>1.82E+09</td>
<td>USGS</td>
</tr>
<tr>
<td>Outflow</td>
<td>1.82E+09</td>
<td>1.82E+09</td>
<td>1.14E+09</td>
<td></td>
</tr>
<tr>
<td>Truckee Canal</td>
<td>--</td>
<td>6.58E+07</td>
<td>3.29E+08</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Transport Rates (g/m²/d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition</td>
<td>50</td>
<td>21</td>
<td>14</td>
<td>Sed.trap data &amp; model calibration</td>
</tr>
<tr>
<td>Resuspension</td>
<td>22.48</td>
<td>17.64</td>
<td>7.91</td>
<td>model calibration</td>
</tr>
<tr>
<td>Burial - U Sed.</td>
<td>27.52</td>
<td>3.36</td>
<td>6.09</td>
<td>particle balance</td>
</tr>
<tr>
<td>Burial - L Sed.</td>
<td>34.52</td>
<td>7.36</td>
<td>6.09</td>
<td>particle balance</td>
</tr>
<tr>
<td>Mixing</td>
<td>5</td>
<td>3</td>
<td>0.1</td>
<td>assumed</td>
</tr>
<tr>
<td>SedB_In</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>model calibration</td>
</tr>
</tbody>
</table>
Table 4.3: Reservoir parameters - Feb, 1995

<table>
<thead>
<tr>
<th>South Basin</th>
<th>Middle Basin</th>
<th>North Basin</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reservoir Dimensions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Area (m²)</td>
<td>6.32E+06</td>
<td>4.61E+06</td>
<td>7.32E+06</td>
</tr>
<tr>
<td>Mean Depth (m)</td>
<td>4.0</td>
<td>4.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Water Volume (m³)</td>
<td>2.50E+07</td>
<td>2.20E+07</td>
<td>6.43E+07</td>
</tr>
<tr>
<td>Active Sediment Area (m²)</td>
<td>5.37E+06</td>
<td>2.99E+06</td>
<td>4.38E+06</td>
</tr>
<tr>
<td>Sediment U Depth (m)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Sediment L Depth (m)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

| **Particle Densities (kg/L)** | | | Mackay et al. (1994) |
| Susp. Particle | 2 |
| Sediments | 2.4 |
| Aerosols | 2.4 |

| **Process Rates (m/h)** | Mackay et al. (1994) |
| Water-air Volatilization | 1 |
| Air-water Absorption | 0.01 |
| Sed.-water Diffusion | 0.0002 |
| Sed.-sed. Diffusion | 1.00E-08 |

| **Particle Properties** | | | EPA |
| Conc. Susp. Particle (mg/L) | 60 | 50 | 14 |
| Vol. Fract. Aerosols | 1.33E-11 |
| Sed.L Porosity | 0.1 |
| Sed.L Porosity | 0.4 |
| Conc. Susp. Part. inflow (mg/L) | 41 |
| Conc.Susp. Part. truckee (mg/L) | 106.5 |

| **Water Flows (m³/y)** | USGS |
| Inflow | 3.14E+08 | 3.14E+08 | 3.14E+08 |
| Outflow | 3.14E+08 | 3.14E+08 | 7.85E+07 |
| Truckee Canal | 7.76E+07 | 3.88E+08 |

| **Particle Transport Rates (g/m²/d)** | Sed.trap data & model calibration |
| Deposition | 40 | 38 | 34.9 |
| Resuspension | 30 | 24.77 | 20 |
| Burial - U Sed. | 10 | 13.23 | 14.9 |
| Burial - L Sed. | 10.06 | 15.11 | 14.9 |
| Mixing | 5 | 3 | 0.1 |
| SedB_In | 0.06 | 1.88 | 0 |

*Note: Bathymetric map by Katzer (1972)*

*Source: EPA, Mackay et al. (1994)*

*EPA* assumed *USGS* Sed.trap data & model calibration particle balance assumed model calibration
<table>
<thead>
<tr>
<th>Source</th>
<th>South Basin</th>
<th>Middle Basin</th>
<th>North Basin</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Area (m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>5.88E+05</td>
<td>4.30E+05</td>
<td>6.83E+05</td>
<td></td>
</tr>
<tr>
<td>Mean Depth (m)</td>
<td>3.5</td>
<td>4.2</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Water Volume (m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>2.04E+06</td>
<td>1.80E+06</td>
<td>5.25E+06</td>
<td>Bathymetric map</td>
</tr>
<tr>
<td>Active Sediment Area (m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>4.71E+05</td>
<td>2.80E+05</td>
<td>4.10E+05</td>
<td>by Katzer (1972)</td>
</tr>
<tr>
<td>Sediment U Depth (m)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sediment L Depth (m)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Particle Densities (kg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Susp. Particle</td>
<td>2.4</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Susp. Sediments</td>
<td>2.4</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Susp. Aerosols</td>
<td>2.4</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Process Rates (m/h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water-air Volatilization</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-water Absorption</td>
<td>0.01</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Sed.-water Diffusion</td>
<td>0.0002</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Sed.-sed. Diffusion</td>
<td>1.00E-08</td>
<td></td>
<td></td>
<td>Mackay et al. (1994)</td>
</tr>
<tr>
<td>Particle Properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc. Susp. Particle(mg/L)</td>
<td>50</td>
<td>40</td>
<td>68.9</td>
<td>EPA</td>
</tr>
<tr>
<td>Sed.U Porosity</td>
<td>0.1</td>
<td></td>
<td></td>
<td>assumed</td>
</tr>
<tr>
<td>Sed.L Porosity</td>
<td>0.4</td>
<td></td>
<td></td>
<td>assumed</td>
</tr>
<tr>
<td>Conc. Susp. Part. inflow(mg/L)</td>
<td>52.7</td>
<td></td>
<td></td>
<td>EPA</td>
</tr>
<tr>
<td>Conc.Susp. Part. truckee(mg/L)</td>
<td>52.7</td>
<td></td>
<td></td>
<td>assumed</td>
</tr>
<tr>
<td>Water Flows (m&lt;sup&gt;3&lt;/sup&gt;/y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflow</td>
<td>3.01E+05</td>
<td>3.01E+05</td>
<td>3.01E+05</td>
<td>USGS</td>
</tr>
<tr>
<td>Outflow</td>
<td>3.01E+05</td>
<td>3.01E+05</td>
<td>3.01E+05</td>
<td>USGS</td>
</tr>
<tr>
<td>Truckee Canal</td>
<td>---</td>
<td>3.50E+05</td>
<td>1.75E+06</td>
<td></td>
</tr>
<tr>
<td>Particle Transport Rates (g/m&lt;sup&gt;2&lt;/sup&gt;/d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>Sed.trap data &amp; model calibration</td>
</tr>
<tr>
<td>Resuspension</td>
<td>29.99</td>
<td>24.83</td>
<td>19.54</td>
<td>model calibration</td>
</tr>
<tr>
<td>Burial - U Sed.</td>
<td>0.0047</td>
<td>0.17</td>
<td>0.46</td>
<td>particle balance</td>
</tr>
<tr>
<td>Burial - L Sed.</td>
<td>0.2247</td>
<td>1.6</td>
<td>0.46</td>
<td>particle balance</td>
</tr>
<tr>
<td>Mixing</td>
<td>5</td>
<td>3</td>
<td>0.1</td>
<td>assumed</td>
</tr>
<tr>
<td>SedB_in</td>
<td>0.22</td>
<td>1.43</td>
<td>0</td>
<td>model calibration</td>
</tr>
</tbody>
</table>
4.3 Mercury Speciation and Sampling Data

Over 90% of total Hg in the Carson River and Lahontan Reservoir, in water and sediments, is strongly bound to particles and sediment (EPA 1996). Figure 4.10 illustrates dissolved (<0.2 µ) and particulate fractions in water sampled in May 1995. Most Hg in the particle occurs as a tightly bound amalgam with gold and silver, and a residual fraction that may include Hg sulfides (Lechler et al. 1994). Less than 1% of total Hg is in elemental gaseous (Hg\(^0\)) or monomethyl Hg (MeHg) forms (EPA 1996).

The model considers three species of Hg in all compartments and phases of the model, elemental gaseous Hg\(^0\) that is highly volatile, MeHg that is bioaccumulative, and the residual fraction of particle bound Hg, (HgR), as discussed above. Since Hg(II) was not analysed in sediment solids, it was not possible to include chemically active Hg(II) as a distinct species in the model. Thus, the Hg(II) values in the dissolved phase were added to HgR values. Table 4.5 lists species fractions calculated from measured Hg concentrations and Table 4.6 summarizes the physical-chemical properties of each species. For residual Hg that is nonvolatile, the key physical-chemical properties are empirically derived partition coefficients, which circumvents the need for exact chemical characterization. The same species concentration fractions are used in for all the basins.

The fraction of MeHg is small and relatively constant over the length of the river (E&E 1992). Figure 4.11 depicts the MeHg measured in the three basins during the sampling periods. MeHg concentrations are highest during September 1994 and decline with increasing Carson River flowrates. Chen et al. (1996) have suggested that elevated concentrations of inorganic Hg could have an inhibiting effect on Hg-methylating microorganisms.

4.4 Steady State Model Formulation

The QWAS model has been formulated for steady-state and unsteady-state conditions. The steady-state model provides a ‘snapshot’ of the event along with insight
Figure 4.10: Dissolved and particulate fractions of Hg in water (May 1995)

Figure 4.11: Methyl Hg concentrations in the reservoir basins as measured by EPA 1996.
Table 4.5: Mercury species concentration fractions in air, water, and sediment

<table>
<thead>
<tr>
<th>Source</th>
<th>Hg $^a$</th>
<th>Residual Hg</th>
<th>MeHg</th>
<th>Hg $^a$</th>
<th>Residual Hg</th>
<th>MeHg</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>0.98</td>
<td>1.00E-12</td>
<td>0.02</td>
<td>1.00E-12</td>
<td>0.97</td>
<td>0.03</td>
<td>Fitzgerald et al. 1991</td>
</tr>
<tr>
<td>WATER</td>
<td>0.003</td>
<td>0.987</td>
<td>0.03</td>
<td>1.00E-12</td>
<td>0.997</td>
<td>0.003</td>
<td>EPA</td>
</tr>
<tr>
<td>PORE WATER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EPA</td>
</tr>
<tr>
<td>SEDIMENT</td>
<td>6.45E-05</td>
<td>0.91</td>
<td>0.09</td>
<td>1.00E-12</td>
<td>0.9995</td>
<td>0.0005</td>
<td>EPA</td>
</tr>
</tbody>
</table>

Table 4.6: Physical-chemical properties of mercury species
(source: Yarwood & Niki, 1990)

<table>
<thead>
<tr>
<th>Hg $^a$</th>
<th>Residual $^2$</th>
<th>MeHg $^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight (g/mol)</td>
<td>200.7</td>
<td>232.65</td>
</tr>
<tr>
<td>Henry's Law Constant (Pa.m$^3$/mol)</td>
<td>488</td>
<td>---</td>
</tr>
<tr>
<td>Vapor Pressure (Pa)</td>
<td>0.246</td>
<td>---</td>
</tr>
<tr>
<td>Melting Point ($^\circ$C)</td>
<td>-38.9</td>
<td>---</td>
</tr>
</tbody>
</table>

1: elemental gaseous mercury
2: particle-bound residual mercury
3: methyl mercury

Table 4.7: Chemical parameters

<table>
<thead>
<tr>
<th>South Basin</th>
<th>Middle Basin</th>
<th>North Basin</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partition Coefficients (L/kg)</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Suspended Particle-water</td>
<td>5.08E+05</td>
<td>5.90E+05</td>
<td>5.08E+05</td>
</tr>
<tr>
<td>Sed. water (mid-basin)</td>
<td>5.49E+05</td>
<td>3.02E+05</td>
<td>1.76E+05</td>
</tr>
<tr>
<td>Sed. water (near-shore)</td>
<td>1.09E+03</td>
<td>1.74E+03</td>
<td>9.08E+02</td>
</tr>
</tbody>
</table>

Z Values

| Z | Air | 0.005 | 0.005 | 0.005 |
|   | WATER | 1.00 | 1.00 | 1.00 |
| SUSPENDED PART. | 1.21E+06 | 1.41E+06 | 1.21E+06 | Calculated |
| SEDIMENT PART. | 1.32E+06 | 7.25E+05 | 4.22E+05 | |
| PORE WATER | 1.00 | 1.00 | 1.00 |

Input Mercury Concentrations (ng/L)

| Air (ng/m3) | 2.30 | Gustin et al. 1984 |

Inflow Carson River:
- dissolved | 32.00 | EPA 1996 |
- suspended particles | 1888.00 | EPA 1996 |

Truckee Canal:
- dissolved | 2.00 | EPA 1996 |
- suspended particles | 44.00 | EPA 1996 |

Initial Equivalences (mol/m$^3$)

| Air | 2.29E-09 | |
| Carson River Inflow | 6.00E-07 | Calculated |
| Truckee Inflow | 6.00E-07 | |
inflow and outflow sources from each compartment are summarized below:

**WATER COLUMN**

**Input sources:**
- particulate and dissolved Hg inflow from Carson River and Truckee Canal.
- atmospheric deposition by wet and dry deposition of particulate Hg, rain dissolution, and adsorption of gaseous Hg$^0$ from air to water.
- particulate Hg resuspended from sediment to water column and dissolved Hg diffusing from pore-water to water column.

**Output sources:**
- particulate and dissolved Hg export via discharge from the Lahontan Dam.
- volatilization of gaseous Hg$^0$.
- deposition of particulate Hg and diffusion of dissolved Hg from water column to porewater.

**UPPER SEDIMENT LAYER**

**Input sources:**
- deposition of particulate Hg and diffusion of dissolved Hg from water column to porewater.
- mixing of particulate Hg and diffusion of dissolved Hg in the pore-water from the lower to the upper sediment layer.

**Output sources:**
- resuspension and diffusion of dissolved Hg from pore-water to water column.
- mixing of particulate Hg and diffusion of dissolved Hg in the pore-water from the upper to the lower sediment layer.
- burial of particulate Hg to the lower sediment layer.

**LOWER SEDIMENT LAYER**

**Input sources:**
- burial of particulate Hg from the upper sediment layer.
- mixing of particulate Hg and diffusion of dissolved Hg in the pore-water from the upper to the lower sediment layer.
Output sources:
- introduction of sediments from deep, buried sediment.
- mixing of particulate Hg and diffusion of dissolved Hg in the pore-water from the lower to the upper sediment layer.
- burial of particulate Hg to the deep, buried sediment.

The processes responsible for ultimately removing Hg from the system are volatilization, export out of the dam and burial to the deep sediments. However, it is hypothesized that Hg from deep, buried sediment enters the system.

### 4.5 Mass Balance Equations

Mercury dynamics in this multi-compartmental multispecies system are described by a series of differential equations. One equation is written for each compartment in each basin, expressing mercury accumulation within that medium as a function of time. In each case, mercury accumulation is expressed as the difference between the incoming and outgoing fluxes. The D Values used here are listed in Table 3.1. The mass balance equations are as follows:

**Water column**

\[
\begin{align*}
\frac{d (V_W Z_{BW} Q_W)}{dt} &= [Q_t (D_t + D_X) + Q_{r}(D_{rT} + D_{rT}) + Q_{a}(D_{M} + D_{C} + D_{Q} + D_{A}) + Q_{su}(D_{R} + D_{SUW})] \\
&- Q_w(D_T + D_V + D_V + D_D + D_{WSL})]
\end{align*}
\]

4.5.1

**Upper sediment layer**

\[
\begin{align*}
\frac{d (V_{SU} Z_{BSU} Q_{SU})}{dt} &= [Q_w(D_D + D_{WSL}) + Q_{SL}(D_{ML} + D_{SL}) - Q_{SU}(D_R + D_{SUW} + D_{BU} + D_{MU} + D_{SU})] \\
\end{align*}
\]

4.5.2

**Lower sediment layer**

\[
\begin{align*}
\frac{d (V_{SL} Z_{BSL} Q_{SL})}{dt} &= [Q_{SU}(D_{MU} + D_{BU} + D_{SU}) + Q_{SB}(D_{SH}) - Q_{SL}(D_{HL} + D_{ML} + D_{SL})] \\
\end{align*}
\]

4.5.3
solved with three unknowns. The steady-state solutions for the equivalences in water, upper sediment and lower sediments are given in equations 4.5.4, 4.5.5, and 4.5.6 below. Since the flow of water in the reservoir is from south to middle to north basin, finally discharging through the dam, the set of differential equations were solved sequentially with the outputs from the south basin forming input data for the middle basin etc. The solutions for equations 4.5.1, 4.5.2 and 4.5.3 are:

\[ Q_w = (Q(D_t + D_x) + ((D_R + D_{SW}) \cdot \text{dumbB})/\text{dumbA}) + (Q_A \cdot (D_A + D_M + D_C + D_Q))/\text{dumbC}) \]

\[ Q_{SU} = (Q_w \cdot (D_D + D_{WS}) + ((D_{SL} + D_{ML}) \cdot D_{SB})/(D_{SL} + D_{ML} + D_{BL}))/\text{dumbA} \]

\[ Q_{SL} = ((Q_{SU} \cdot (D_{SU} + D_{BU} + D_{MU} + D_{R})) + D_{SB})/(D_{SL} + D_{ML} + D_{BL}) \]

\[ \text{dumbA} = (D_{SU} + D_{MU} + D_{BU} + D_{SW} + D_R) - ((D_{SU} + D_{MU} + D_{BU}) \cdot (D_{SL} + D_{ML})/(D_{SL} + D_{ML} + D_{BL})) \]

\[ \text{dumbB} = (D_{SL} + D_{ML}) \cdot D_{SB}/(D_{SL} + D_{ML} + D_{BL}) \]

\[ \text{dumbC} = (D_J + D_V + D_{WS} + D_P + D_Y) - ((D_{WS} + D_D) \cdot (D_R + D_{SW})/\text{dumbA}) \]

The computer program is written in Borland C++ language in a Windows environment and suitable to run on a IBM PC compatible. The steady-state model for May 1995 is listed in Appendix A.

### 4.6 Model Calibration and Testing

The models were primarily parameterised and calibrated using the EPA 1996 data for the three sampling events. Hg equivalence in air was calculated from concentrations obtained from Gustin et al. (1994) and concentrations from Miller et al. (1994) were used for lower sediment layer and buried sediments. Table 4.7 lists the chemical parameters and equivalences used in the model. The calibration criterion was correspondence between measured (EPA 1996) and estimated Hg concentrations in the water column and sediment. The parameter values adjusted to maximize this correspondence were sediment deposition, resuspension and introduction of contaminated sediments. The values for sediment movement were constrained by the overall particle balance in the system and basin.
For May 1995, estimated water concentrations are within 30% of measured values (EPA data), and estimated sediment concentrations in the south and middle basins are within 35% of measured concentrations (EPA 1996; Miller et al. 1995). The discrepancy between estimated and measured sediment concentrations in the north basin is about a factor of three for the data of Miller et al. (1995). The measured sediment concentration in this study of 400 ng/g, is an order of magnitude lower than that reported by Miller et al. (1995) and illustrates the spatial heterogeneity in sediment concentrations.

For February 1995, the water column concentrations are under estimated for the south and middle basins by 55% and 35%, respectively. However, for the north basin, the water column concentrations are over-estimated by 6 times. The sediment concentrations are within 40% of the observed values for the middle and south basins. The model estimated sediment concentrations in the north basin are about 4.5 times the measured value and 3 times the Miller et al. 1995 values, because the model is calibrated sustaining the particle balance and the model results at this level overestimate measured values. For September 1994, the estimated sediment concentrations are about twice the measured values in all the basins. The water column concentrations are 40, 10 and 20% higher in the south, middle and north basin, respectively compared to the measured values.

As an independent test, the model was run with data specified by Cooper et al. (1985) for May-June 1983 and Bonzongo et al. (1996) who sampled the reservoir in May 1994. Estimated values were within 30% of reported concentrations (Table 4.8). These results are promising as the agreement was achieved by changing only the river flowrate and input Hg loading in both cases, while maintaining the other parameter values. The correspondence was better for the May-June 1983 data compared to the June 1994 data, as the water flowrates in Carson river and water volumes in the Lahontan reservoir were
Figure 4.12: Comparison of measured and model estimated Hg concentrations in water column

<table>
<thead>
<tr>
<th></th>
<th>Model Results</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>south basin</strong></td>
<td>477</td>
<td>528±1</td>
</tr>
<tr>
<td></td>
<td>1295</td>
<td>2788±1</td>
</tr>
<tr>
<td></td>
<td>2911</td>
<td>1671±1</td>
</tr>
<tr>
<td><strong>middle basin</strong></td>
<td>427</td>
<td>475±50</td>
</tr>
<tr>
<td></td>
<td>631</td>
<td>991±200</td>
</tr>
<tr>
<td></td>
<td>2166</td>
<td>2067±1</td>
</tr>
<tr>
<td><strong>north basin</strong></td>
<td>315</td>
<td>210±9</td>
</tr>
<tr>
<td></td>
<td>182</td>
<td>32±0.6</td>
</tr>
<tr>
<td></td>
<td>691</td>
<td>493±0.1</td>
</tr>
</tbody>
</table>

Notes:
1. Water concentrations in ng/L.
2. Measured concentrations refer to EPA 1994-95 sampling events. Values are mean values with standard deviation for n=2.
Figure 4.13: Comparison of measured and estimated sediment Hg concentrations. Values are in ng/g.

<table>
<thead>
<tr>
<th>Model Results</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>11597 - 54437</td>
<td>21336 ± 5381</td>
</tr>
<tr>
<td></td>
<td>(24204 - May</td>
</tr>
<tr>
<td></td>
<td>15128 - Feb</td>
</tr>
<tr>
<td></td>
<td>24675 - Sep)</td>
</tr>
<tr>
<td>sediment -U</td>
<td></td>
</tr>
<tr>
<td>16319 - 55341</td>
<td>40000 *</td>
</tr>
<tr>
<td>sediment -L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>south basin</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Results</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>18115 - 22726</td>
<td>26054 ± 5203</td>
</tr>
<tr>
<td></td>
<td>(30371 - May</td>
</tr>
<tr>
<td></td>
<td>27516 - Feb</td>
</tr>
<tr>
<td></td>
<td>20276 - Sep)</td>
</tr>
<tr>
<td>sediment -U</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Results</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>9847 - 13385</td>
<td>2134 ± 1659</td>
</tr>
<tr>
<td></td>
<td>(369 - May</td>
</tr>
<tr>
<td></td>
<td>2371 - Feb</td>
</tr>
<tr>
<td></td>
<td>3663 - Sep)</td>
</tr>
<tr>
<td>sediment -U</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model Results</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>9847 - 13385</td>
<td>40000 *</td>
</tr>
<tr>
<td>sediment -L</td>
<td>north basin</td>
</tr>
</tbody>
</table>

Note: Model results are reported as concentration range. Measured values are mean values with standard deviation for n=3.
Spatially, the model accounts for declining Hg concentrations in water column from the south to north basin. Measured sediment concentration variations depicted in the Figure 4.13 represent more spatial variability than seasonal trends as such large variations in sediment concentrations are unlikely over such short periods of time. The large standard deviation associated with the mean values is indicative of the large spatial heterogeneity in the sediment concentrations within and among the basins. The sediment concentrations in south and middle basin are the same order of magnitude and an order of magnitude higher than the north basin. The deviations of measured and estimated values are within the margin of error associated with sampling and modeling of such highly variable systems.
Table 4.8: Comparison between measured and estimated water and sediment concentrations. Measured data from Cooper et al. (1985) and Bonzango et al. (1994).

<table>
<thead>
<tr>
<th></th>
<th>Water Inflow (m³/y)</th>
<th>Water Outflow (m³/y)</th>
<th>Input Conc. (ng/L)</th>
<th>Conc. in Water Observed (ng/L)</th>
<th>Conc. in Water Estimated (ng/L)</th>
<th>Conc. in Sediment Observed (µg/g)</th>
<th>Conc. in Sediment Estimated (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPA May 1995</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-- south basin</td>
<td>1.82E+09</td>
<td>1.82E+09</td>
<td>1932</td>
<td>528</td>
<td>477</td>
<td>24 - 35</td>
<td>20</td>
</tr>
<tr>
<td>-- middle basin</td>
<td>1.88E+09</td>
<td>1.88E+09</td>
<td></td>
<td>475</td>
<td>427</td>
<td>25 - 30</td>
<td>21</td>
</tr>
<tr>
<td>-- north basin</td>
<td>2.21E+09</td>
<td>1.14E+09</td>
<td></td>
<td>218</td>
<td>315</td>
<td>0.4 - 4</td>
<td>13</td>
</tr>
<tr>
<td><strong>EPA Feb 1995</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-- south basin</td>
<td>3.14E+08</td>
<td>3.14E+08</td>
<td>2541</td>
<td>2788</td>
<td>1295</td>
<td>12 - 15</td>
<td>21</td>
</tr>
<tr>
<td>-- middle basin</td>
<td>3.92E+08</td>
<td>3.92E+08</td>
<td></td>
<td>991</td>
<td>631</td>
<td>22 - 28</td>
<td>13</td>
</tr>
<tr>
<td>-- north basin</td>
<td>7.02E+08</td>
<td>7.85E+07</td>
<td></td>
<td>32</td>
<td>182</td>
<td>2 - 4</td>
<td>11</td>
</tr>
<tr>
<td><strong>EPA Sept 1994</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-- south basin</td>
<td>3.01E+05</td>
<td>3.01E+05</td>
<td>2231</td>
<td>1671</td>
<td>2911</td>
<td>22 - 25</td>
<td>58</td>
</tr>
<tr>
<td>-- middle basin</td>
<td>6.51E+05</td>
<td>6.51E+05</td>
<td></td>
<td>2067</td>
<td>2166</td>
<td>18 - 21</td>
<td>53</td>
</tr>
<tr>
<td>-- north basin</td>
<td>2.05E+06</td>
<td>3.01E+05</td>
<td></td>
<td>493</td>
<td>691</td>
<td>3 - 4</td>
<td>10</td>
</tr>
<tr>
<td><strong>Cooper et al. (1985)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 1983-Dec.1984</td>
<td>1.07E+09</td>
<td>7.60E+08</td>
<td>2200</td>
<td>100+240</td>
<td>138</td>
<td>1.8+0.8</td>
<td>6</td>
</tr>
<tr>
<td><strong>Bonzango et al. (1994)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-- May, 1994</td>
<td>2.83E+08</td>
<td>4.06E+08</td>
<td>1471</td>
<td>57+0.77</td>
<td>67</td>
<td>--</td>
<td>3</td>
</tr>
<tr>
<td>-- June, 1994</td>
<td>8.21E+07</td>
<td>6.33E+08</td>
<td>824</td>
<td>158+15</td>
<td>50</td>
<td>--</td>
<td>2</td>
</tr>
</tbody>
</table>
5. Unsteady-State Model Description, Parametrization and Calibration

The steady-state models for three sampling events described in Section 3 gave snapshots of the dominant processes, flows and particle dynamics in the Lahontan Reservoir. However, the system is not at steady-state, because of system variability and in-place pollution. Thus, to make long term predictions of system dynamics with a view towards mitigation and remediation, a time dependent model was created to better approximate reality. The unsteady-state (USS) model connects the snapshots through time dependent functions of reservoir volume, water flowrates, Hg concentrations, and particle movement rates. Due to the high variability of the system and considerable uncertainty in the measured and predicted parameters in the steady-state models, the unsteady-state model results are likely to have high degree of uncertainty. However, it will help us predict trends in Hg concentrations over time from which better informed decisions can be made regarding environmental rehabilitation.

5.1 Unsteady State Model Parametrization and Formulation

The QWASI model formulation is similar in form for both the steady and unsteady-state models. Several D values in the USS model are time dependent equations derived by fitting curves to the three point estimates used in the steady-state versions. The equations used for describing the particle transport terms, suspended particle concentrations, basin volumes and water flows are summarised in Table 5.1.

Mercury dynamics in this multi-compartmental, multispecies system are described by the series of differential equations in 4.5.1 to 4.5.3. These set of equations were solved numerically using Euler’s method. As both volumes and equivalence change with time, the numerical solution required defining initial boundary conditions for both values. The initial values corresponded with the September values for the respective parameters and the
Table 5.1: Equations used in the USS model to describe the various time dependent parameters. “t” denotes time in hours.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Volume</td>
<td>$= (-1655) + (24<em>t) - (0.0251218</em>t^2) + (0.00000900194*t^3) -$</td>
</tr>
<tr>
<td></td>
<td>$(0.00000000105372<em>t^4) + (0.000000000000378275</em>t^5)$</td>
</tr>
<tr>
<td>Carson River Flow</td>
<td>$= 144897000 + (56464.8<em>t) - (37.1877</em>t^2) + (0.0141575*t^3) -$</td>
</tr>
<tr>
<td></td>
<td>$(0.00000202403<em>t^4) + (0.0000000000917502</em>t^5)$</td>
</tr>
<tr>
<td>Truckee Flow</td>
<td>$= (1.75E06 + (1.69441E05<em>t) - (14.4756</em>t^2) - (0.000444499*t^3)) /$</td>
</tr>
<tr>
<td></td>
<td>$8760$</td>
</tr>
</tbody>
</table>

South Basin

| Suspended Particles | $= 90.7 + (0.0215278*t) - (8.38346E-06*t^2) + (6.58532E-10*t^3)$                  |
| Deposition          | $= (30 + (0.0030039*t) + (1.94073E-07*t^2) - (5.71912E-11*t^3))/24$            |
| Resuspension        | $= (29 + (0.00411898*t) - (1.69288E-06*t^2) + (1.35911E-10*t^3))/24$           |
| Sed_back            | $= (0.22 - (0.000385472*t) + (1.56273E-07*t^2) - (1.24835E-11*t^3))/24$        |

Middle Basin

| Suspended Particles | $= 75.0 + (0.0140987*t) - (6.51423E-06*t^2) + (5.4395E-10*t^3)$                  |
| Deposition          | $= (25 + (0.0139107*t) - (3.86342E-06*t^2) + (2.56178E-10*t^3))/24$            |
| Resuspension        | $= (24.5 + (0.00113132*t) - (9.09894E-07*t^2) + (8.60084E-11*t^3))/24$         |
| Sed_back            | $= (1.43 - (0.000802357*t) + (4.25833E-07*t^2) - (3.69855E-11*t^3))/24$        |

North Basin

| Suspended Particles | $= 64 - (0.0182256*t) + (1.77815E-06*t^2) + (2.3622E-11*t^3)$                  |
| Deposition          | $= (20 + (0.0167183*t) - (4.74669E-06*t^2) + (3.19207E-10*t^3))/24$            |
| Resuspension        | $= (19.54 + (0.00677945*t) - (2.7229E-06*t^2) + (2.16758E-10*t^3))/24$         |
| Sed_back            | $= 0.0$                                                                    |

Note: As constrained by reservoir particle balance, the burial rates was calculated as:

$Buru[basin] = Dep[basin] - Res[basin]$; and

initial equivalences and volumes fixed the amount of Hg in the system. The equivalences in air (Gustin et. al 1994) and introduced sediments (Miller et. al. 1995) were treated as constants. A fixed time step of 1 hour was used and the equations were solved simultaneously. The USS solutions for equations are contained in Appendix B which lists the computer program written in Borland C++™.

5.2 Model Calibration

Calibration of the unsteady-state model was more difficult than steady-state model as there were numerous terms requiring estimation. The basis for calibration was correspondance of the results with the measured data (achieved by calibrating these initial values). The sediment concentrations were also affected by the concentration of introduced, buried sediments. Hence this equivalence also needed calibration to give better correspondance of sediment values.

Figure 5.1(Series 1) depicts water and sediment concentrations as predicted by the USS model in the middle basin. Water column Hg concentrations rise to 3500 from 1700 ng/L, upper sediment concentrations rise to 1.2E05 from 2E04 ng/g and lower sediments increase to 1.60E05 from 9000 ng/g in 10 years. The increase of water and sediment concentration is due to the input of buried sediments (infinite source) into the lower sediments and the assumption that the chemicals partition instantaneously into the various phases according to the specified partition coefficients. In reality, as the Hg concentrations in sediments rise and vertical mixing takes place, the contribution from buried sediments will diminish. Thus, over time, there may be reductions in Hg concentration in sediments, due to net sediment burial and inaccessibility of deep buried Hg. Additionally, in nature, sediments take long time to respond to changes to input loadings. To simulate a reduced sediment contribution with time, the buried sediment concentration was decreased by an assumed value of 5% per year.
Legend: Series1: constant Hg conc in deep sediments
Series3: 5% linear reduction in Hg conc of deep sediments

Figure 5.1: Comparison of USS model estimates assuming a constant Hg concentration in deep sediments and reducing the concentration by 5% annually.
The results achieved by this reducing function are depicted in Fig 3.1A, where the rise in concentration in water column and sediment concentrations are less than those in the infinite source situation. The concentrations predicted are likely to be within an order of magnitude. The model sensitivity to various parameters is discussed with model results in the subsequent section.

Another, significant observation of this unsteady-state model is the inadequacy of the QWASI model to make predictions of sediment concentrations. The seasonal variations appearing in sediment concentrations are not realistic as sediment concentrations do not vary seasonally. However, the QWASI model is unable to address this due to the assumptions of instantaneous partitioning of chemicals in a phase and the existence of equilibrium within phases.
6. Results and Discussions

The steady-state model results are discussed individually for the three snapshots, followed by, the unsteady-state model results. A sensitivity analysis has been done to ascertain the dominant parameters affecting the model results for steady- and unsteady-state models. Lastly, the reservoir dynamics are discussed synthesizing all results.

6.1 Snapshot Results

6.1.1 May 1995 Results

As shown in Figure 6.1, the principal source of Hg to the reservoir is the Carson River (>99.9 %) with minimal contributions from the Truckee Canal and atmospheric deposition. More than 97.5% of the incoming Hg is associated with the particles and of this, over 90% is retained in the reservoir sediments. In comparison, about 65% (140 g/d) of dissolved Hg in water is retained in the water column. The remainder is exported via the dam outlet. Volatilization losses are extremely small at 0.2 g/d. This is in agreement with findings of Gustin et al. (1996) that either Hg" volatilising from the water is diluted at their measurement site (100 m from the reservoir) or that the flux from the reservoir is low.

It is observed that only about 2-3% of Hg entering the reservoir is dissolved whereas dissolved Hg forms about 7-8% of total Hg in the reservoir. The higher proportion of dissolved Hg in the reservoir could be attributed to loss of the particulate fraction through deposition. High concentrations of Hg in water column and sediments are encountered in south and middle basins. The lower north basin Hg concentrations are attributable to burial of Hg-rich particles in the previous basins and dilution with ‘cleaner particles’ from the Truckee Canal.
Figure 6.1: Estimated rates of total mercury transport for May 1995. Rates expressed in g/d.
not be maintained given the present loadings from the Carson River, particularly in the middle and south basins. Two possibilities are suggested to account for the discrepancy.

- the model is either incorrect or inappropriately parameterized, or
- additional loadings contribute to measured concentrations.

To examine the first possibility, the model was assessed with the data of Cooper et al. (1985) and Bonzongo et al. (1996), as discussed in Section 4.3. The model performed satisfactorily. Given the experience and confidence of carrying out modeling for single chemicals (Ling et al. 1993, Diamond et al. 1994) and mercury (Diamond, submitted), and the results presented here, it is believed that the first possibility is unlikely. As regards the second possibility, additional loadings could be due to atmospheric deposition, in-place pollution due to contaminated sediment sources (Diamond 1995), or input sources that have not been considered (Diamond et al. 1996). For Lahontan Reservoir, atmospheric deposition is unlikely, as discussed above. Additional high loading conditions are a possibility but the model simulates a 1 in 50 year high loading event (May 1995) with water flows twice the normal seasonal flows. The final possibility, contaminated sediments acting as a source, is likely considering the high concentration of Hg in the sediments and the “shrink-swell” process described for sediment upward movement by Miller et al. (1995). This has been discussed in detail in Section 3.2.3.

To achieve correspondence between measured and estimated sediment concentrations, it was hypothesized that 6.45 kg of Hg from 105 t/d of lower sediment layers is remobilized and introduced in the south basin and about 33 t/d of sediments with 2.2 kg of Hg is introduced to the middle basin. This sediment and its Hg load are introduced into the water column through sediment resuspension. The quantity of resuspended material and introduced sediments are equal in south basin, and resuspended material is about 1.4 times the introduced material in middle basin. Sediment resuspension is a calibrated term constrained by Hg concentrations and a particle balance of the system. Sediment mixing between layers is suggested to be responsible for moving the Hg rich particles to the upper
seaimens. whereas model results suggest buried sediment introduction in south and middle basins, this is not the case for the north basin that, unlike the previous two basins, is perpetually filled. It is hypothesized that as cleaner surface sediments continue to settle in the basins and the process of mixing continues, the concentration of the buried sediments will decline over time and an overall reduction in Hg concentrations in sediment particles will occur.

The Hg partition coefficients were of the same order of magnitude in water column and sediments. Further, the Hg concentrations are very low in water and pore water relative to sediments (EPA 1996). The driving force available for diffusion between sediment and water column is minimal. This is in contradiction to uncontaminated systems in which sediment partition coefficients are typically in order of magnitude less than water column values (Hurley et al. 1994a), leading to potentially significant diffusive fluxes (e.g. Krabbenhoft and Babiarz 1992).

Individual Hg species exhibit different behaviour from total Hg, as illustrated in Figure 6.2 to 6.4. It is observed that only 2 g/d (~0.02%) of incoming total Hg of 9.6 kg/d is elemental Hg\(^0\). Hg(II) has been observed to be reduced to Hg\(^\text{II}\) by a number of bacteria and fungi (Olsen et al. 1981) and by humic substances (Xiao et al. 1991). In the Lahontan Reservoir, Hg reduction is limited by lack of availability of reactive Hg(II) and possibly by low concentrations of humic substances. Fitzgerald et al. (1994) hypothesized that Hg\(^\text{II}\) volatilization is a release mechanism that reduces the total amount of Hg amounts in a lake. With virtually no Hg\(^\text{II}\) in the reservoir (Figure 6.2), this avenue for Hg release is not available in the reservoir.

Only about 0.3% (40 g/d) of input Hg is MeHg (Figure 6.3). The Truckee Canal and the ‘buried sediment’ introductions are suggested to contribute 4 g/d of MeHg each. However, these estimates are based on the fraction of the species in the input from the Carson River and sediment layers and could be in error. Further, it is observed that MeHg constitutes about 0.5% of total Hg in the water column and 0.1% of Hg in the sediments.
Figure 6.2: Estimated rates of elemental mercury transport for May 1995. Rates expressed in g/d.
Figure 6.3: Estimated rates of monomethyl mercury transport for May 1995. Rates expressed in g/d.
Model estimates indicate that there is probably no net gain or production of MeHg in the system at the expense of HgR or Hg\(^6\). The MeHg in the reservoir can be accounted for by inputs from the Carson River. A mass balance of MeHg in the reservoir indicates that totally 48 g/d enters the basin with a net export of 14 g/d, resulting in a net loss of 34 g/d within the reservoir. The total mass of MeHg involved is less than 0.5% of the total Hg mass and may be within the margin of uncertainty rather than be indicative of actual losses or interconversion. Further, error could be introduced since the model does not account for biotic uptake, whereas which is a dominant fate for MeHg (Lindqvist et al. 1985; Zillioux et al. 1993; Fitzgerald and Clarkson 1991).

The fate of residual Hg movement is similar to any particle-bound metal, with burial being the principal loss mechanism (Figure 6.4). Since more than 97.5% of Hg in the reservoir is particle-bound residual Hg, the reservoir behaves like a sink with more than 90% of the incoming Hg being retained in the reservoir. This stresses the need to understand the nature of Hg associated with the particles. The model suggests that Hg in the Lahontan Reservoir undergoes minimal interconversion with resultant minimal volatilization and methylation. The mineralogy of Hg in the reservoir is apparently the main factor controlling Hg fate.

6.1.2 February 1995 Results

As shown in Figure 6.5, in February like May, the principal source of Hg is the Carson River (>95 %) with about 5% contribution from the Truckee Canal and negligible atmospheric deposition. Flow rates during February are an order of magnitude lower and loadings are only 22% of the May levels. In May, the Truckee Canal flow was an order of magnitude lower than the Carson River flow whereas in February, the Truckee flow is of the same order of magnitude as the Carson River flow rate, therefore higher particle loads
Figure 6.4: Estimated rates of residual mercury transport for May 1995. Rates expressed in g/
Figure 6.5: Estimated rates of total mercury transport for February 1995. Rates expressed in g/d.
February than in May (EPA 1996). The canal contributes only 5% of Hg loadings. As in May, more than 97.5% of the incoming Hg is associated with the particles and of this over 98% are retained in the reservoir sediments. Volatilization losses are extremely small at 0.2 g/d. Thus, the reservoir continues to act as Hg repository.

Elemental mercury amounts are negligible in the input as well as in the basins. As regards MeHg, the Carson River input is 9 g/d (0.4%). With inputs from the inflow and resuspension of 14 g/d in the south basin, 120 g/d of deposition and 31 g/d of export, production of 106 g/d in the water column is estimated (Figure 6.6). Further, in the middle and north basins, a production of 15 and 27 g/d is observed. Thus, model results indicate MeHg is produced in water column, suggesting net methylation in the reservoir at low flows. The residual Hg behaviour is similar to that observed during May, with burial being the principal loss mechanism.

### 6.1.3 September 1994 Results

As shown in Figure 6.7, the September flow rates and Hg loadings are about 4 orders of magnitude less than the previous two sampling events. The south and middle basins had minimal water resulting in isolated shallow pools, with much of the sediments exposed and subject to drying. The north basin remained full. Deposition and resuspension are estimated at about 2 orders of magnitude higher than the loadings in order to sustain the suspended particle concentrations and the particle balance. The total Hg input is 2 g/d through the Carson River and this amount may represent the uncertainty in measurement rather than the absolute value because flowrates in the river were not measurable. Model results suggest introduction of Hg from deep buried sediments of 6 g/d and 26 g/d in south and middle basin respectively. These amounts are twice and 13 times the input in south and middle basin respectively. This suggests high flux of sediment particles in the reservoir even at low flows and is consistent with the mechanistic basis of the sediment mixing process.
Figure 6.6: Estimated rates of monomethyl mercury transport for February 1995. Rates expressed in g/d.
Figure 6.7: Estimated rates of total mercury transport for September 1994. Rates expressed in g/d.
results are in apparent contradiction to suggestions that warm water temperatures and low Hg concentrations should favor net methylation (Cooper et al., 1985; Chen et al., 1996; Rudd, 1995). However, net methylation is low and is within the range of uncertainty.

6.2 Steady-State Model Sensitivity Analysis

Uncertainty in model parameter values and model structure are endemic to modeling. My ability to draw conclusions concerning Hg behaviour in the Lahontan Reservoir is determined by the scenario being modeled and the accuracy of the data being used. In this case, I have modeled Hg dynamics under three steady-state scenarios considering the seasonal low, medium and high Hg loadings. However, the low was at the end of a 10 year drought and the high was a 1 in 50 year event. Although, the conditions were extreme, but the steady-state results are useful to understand the picture at a given moment in time. Further, an unsteady-state model integrating these three models was also created, but due to the extremities of the data and collected at three times in a year, the results may be more uncertain. To generate a long term predictive model, long-term data on the system are required to better parameterize and calibrate the model with more representative results.

To address these limitations, a sensitivity analysis was performed to examine the response of the model estimates to uncertainty and variability in parameter values used in the steady-state models. The magnitude of variability and uncertainty is summarized qualitatively in Table 6.1. For the sensitivity analysis, I doubled parameter values in all three basins simultaneously, a factor that is probably within the range of observed variability. The analysis did not consider the interaction amongst the variables, but was carried out by doubling of one variable at a time. Figure 6.8 illustrates the results of this analysis for May 1995 steady-state model in south basin. The values are expressed in terms of change in total Hg water and sediment concentrations expressed as percentage deviations from the base case.
Table 6.1: Degree and reasons for uncertainties in parameters used in the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>Reasons for uncertainty</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>River Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Water Inflow</td>
<td>USGS gauge</td>
<td>System variability</td>
<td>high</td>
</tr>
<tr>
<td>2 Water Outflow</td>
<td>USGS gauge</td>
<td>Dam operation</td>
<td>high</td>
</tr>
<tr>
<td>3 Truckee Inflow</td>
<td>USGS gauge</td>
<td>System variability</td>
<td>high</td>
</tr>
<tr>
<td><strong>Particle Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 TSS inflow</td>
<td>EPA</td>
<td>System variability</td>
<td>medium</td>
</tr>
<tr>
<td>2 TSS basins</td>
<td>EPA</td>
<td>System variability</td>
<td>medium</td>
</tr>
<tr>
<td>3 TSS Truckee</td>
<td>EPA</td>
<td>Insufficient data</td>
<td>low</td>
</tr>
<tr>
<td>4 Deposition rate</td>
<td>EPA and model</td>
<td>Insufficient data</td>
<td>low</td>
</tr>
<tr>
<td>5 Resuspension rate</td>
<td>EPA and model</td>
<td>Insufficient data</td>
<td>low</td>
</tr>
<tr>
<td>6 Mixing</td>
<td>Calibration</td>
<td>No data</td>
<td>low</td>
</tr>
<tr>
<td>7 Sediment introduction</td>
<td>Calibration</td>
<td>No data</td>
<td>low</td>
</tr>
<tr>
<td>6 Burial rates</td>
<td>Calibration</td>
<td>No data</td>
<td>low</td>
</tr>
<tr>
<td><strong>Mercury Concentrations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Air</td>
<td>Literature</td>
<td>Insufficient data</td>
<td>low</td>
</tr>
<tr>
<td>2 Water inflow</td>
<td>EPA</td>
<td>System variability</td>
<td>high</td>
</tr>
<tr>
<td>3 Basins - water</td>
<td>EPA</td>
<td>System variability</td>
<td>high</td>
</tr>
<tr>
<td>- sediments</td>
<td>EPA/EPA/</td>
<td>System variability</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Miller et al. 1995</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mercury Speciation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Water</td>
<td>EPA</td>
<td>Analytical</td>
<td>high</td>
</tr>
<tr>
<td>2 Suspended particles</td>
<td>EPA</td>
<td>Analytical</td>
<td>medium</td>
</tr>
<tr>
<td>3 Bottom sediments</td>
<td>EPA</td>
<td>Analytical</td>
<td>medium</td>
</tr>
<tr>
<td>4 Pore water</td>
<td>EPA</td>
<td>Analytical</td>
<td>high</td>
</tr>
</tbody>
</table>
Figure 6.8: Sensitivity of mercury water and upper sediment concentrations in south basin to doubling parameter values for steady-state model for May 1995.
Hg loading to the system, namely input concentration and water flow rate. The water flow rates and input concentrations have been measured accurately but the measurements were taken at Churchill gauge, about 6 km from the Carson River inlet to the delta at the mouth of south basin. This difference could be significant if extensive particle movement and mobilization or deposition occurs in between Churchill gauge and the south basin inlet. The reservoir area being doubled halves water and sediment concentrations as expected. Basin volumes are also highly variable temporally, with south basin being dry during February and September and middle basin being dry in September and having very little water during February. Data available was for the reservoir volume but not volumes of each basin, nor were basin areas available. Basin areas affect sediment areas and the particle transport rates e.g deposition, burial and buried sediment introductions. Hence, considerable uncertainty surrounds the basin area and volume as the water levels fluctuate, evaporation losses may be high and siltation occurs over time.

As expected, doubling the concentration of suspended particles increases the Hg water concentration by almost 60% and decreases sediment concentrations by about 20% as more Hg remains in water. The suspended particle concentrations can be measured accurately, but there is considerable spatial as well as temporal variability. Particle movement rates are much more uncertain as they are more difficult to measure and estimate. Doubling deposition rates halves the water concentration and increases sediment concentration by 15%, as more Hg is delivered to the sediments. Doubling resuspension causes the reverse phenomenon, wherein more Hg is reintroduced into the water column, raising the water concentration by 40% and reducing sediment concentrations by 10%. However, this increase in water column concentration in the south basin is lower than expected as more Hg is exported with water to the middle basin.

Within the sediments, doubling the mixing rates between upper and lower sediment layers increases concentrations by 5 to 10% and less is lost through burial. Doubling buried sediment introductions increase the sediment concentrations by about 10%. The
parameters of mixing and sediment introductions are calibrated parameters and need further investigation to improve model estimates.

6.3 Unsteady-state Model Results

The unsteady-state (USS) model is the integration of three seasonal snapshots as discussed earlier. The unsteady-state model results first highlight the seasonal variations in the Hg dynamics and secondly, are useful for making long term predictions of Hg concentrations in water column and sediments.

USS model results have been estimated assuming Hg concentrations, Carson River and Truckee Canal flowrates varying seasonally, in conformation to the steady-state variations, with this variation being constant over the years. For modeling purposes, the outlet water flow rate from the reservoir was computed based on water balance of input from the Carson River and Truckee Canal reduced by evaporation to maintain the water balance. In reality, the outlet from the reservoir is controlled by dam operations based on irrigation needs. Over a year, the net water balance is maintained, i.e. inputs from the Carson River and Truckee Canal are equal to dam outflows and estimated evaporation losses, however, the asynchronous input and output flows were not included in the model.

Hg concentrations in the water column of all basins indicate seasonal variations and increase in concentrations over 10 years. The USS model estimates the Hg concentration in the water column in south basin to increase from 600 to 1700 ng/L in 1st year, to 1000 to 3000 ng/L in 10th year (Figure 6.9). The variation in Hg concentrations in middle and north basin is from 400 to 1800 ng/L in 1st year to 900 to 3200 ng/L in 10th year and from 10 to 900 ng/L in 1st year to 50 to 2000 ng/L in the 10th year respectively (Figures 6.10 and 6.11). The annual average concentrations rise from 1050 to 1700 ng/L in south, 650 to 1800 ng/L in middle, and 150 to 600 ng/L in the north basin, respectively (Figures 6.12 to 6.14). The rate of increase is greatest in north basin (300%), followed by middle basin (200%) and south basin (60%). Perhaps the model estimates such rapid changes in concentrations
Figure 6.9: Estimated Hg concentrations in south basin in water column and sediments illustrating the seasonal variations and the long term behaviour.
Figure 6.10: Estimated Hg concentrations in middle basin in water column and sediments illustrating the seasonal variation and the long term behaviour.
Figure 6.1: Estimated Hg concentrations in north basin in water column and sediments illustrating the seasonal variation and the long term behaviour.
Figure 6.12: Estimated average Hg concentrations in south basin in water column and sediments.
Figure 6.13: Estimated average Hg concentrations in middle basin in water column and sediments over 10 years.
Figure 6.14: Estimated average Hg concentrations in north basin in water column and sediments.
used to parametrize the model, namely the three sampling periods included May 1995 data that was in a 50 year high loadings event and Sept 1994 that came at the end of a 10 year drought event. Therefore, the data may not be reasonable for long term projections.

As the behaviour of Hg in middle and south basins are similar and Hg governing mechanisms being different in north basin, I will restrict my discussions to results from south and north basin. Figure 6.9 indicates variation in the upper sediments within a year is from 9000 to 20000 ng/g in the 1st year to 17000 to 37000 ng/g in the 10th year in south basin. This indicates a doubling of concentrations in 10 years. Lower sediments in south basin vary from 20000 to 40000 ng/g in the 1st year to 60000 to 100000 ng/g in the 10th year, indicating a rise of about 2.5 times in 10 years. Compared to this, in the north basin, the upper sediments vary from 450 to 1500 ng/g in the 1st year to 4000 to 9000 ng/g in the 10th year (Figure 6.11), indicating a rise by an order of magnitude. Lower sediments vary between 800 to 1600 ng/g in the 1st year to 1400 to 3000 ng/g in the 10th year, indicating a rise of 2 times. The model results also indicate seasonal variations of sedimentary Hg concentrations, however, these variations are due to the model estimations being closely associated to water column Hg concentrations and the sampling events having captured extremities in temporal variation. In reality, sediment Hg concentrations are not likely to show such high variations within seasons.

The long term pattern of increases in sediments and water column agrees with our understanding of system behaviour: Hg-rich particles move downstream from their primary location of deposition in the south basin and delta towards the north basin. Concentrations rise relatively more in north basin than south basin as concentrations equalize in the basins and since the north basin is the terminus of these particles. Lower sediment concentrations increase in south and middle basin, influenced by the introduction of Hg-rich deep buried sediments. The upper sediment concentrations do not rise proportionately as the upward movement of Hg bearing sediment particles is governed by mixing between the two layers and this term was calibrated based on steady-state model
Upper sediments are recipients of the Hg-bearing particles from the downstream basins and exhibit an order of magnitude rise in Hg sediment concentrations. The north basin lower sediment Hg concentrations are governed by net burial, and insufficient mixing between the sediment layers and show moderate increase in Hg concentration.

To address the uncertainty introduced by unusually high loadings in May, USS model was used to make long-term projections of Hg behaviour in the reservoir with reductions in Hg loading from the Carson River. Model was run with one time reductions in Hg loadings of 50% and 90% in Carson River inflow, i.e. in place of the present 4000 kg/yr of Hg input from the River, the model was run with loadings of 2000 kg/yr and 400 kg/yr, with present water and sediment concentrations for initialization. These reductions are within the range of temporal variations in loading observed in the reservoir. The results for north and south basin are indicated in Figures 6.15 and 6.16 respectively. The water column concentrations fall by 15 and 33%, respectively, in north basin for loading reductions of 50 and 90%. In south basin, the reductions in Hg concentration in water column were 10 and 20%, respectively. The upper sediment concentrations decline by 10 and 20% in north basin and 5 and 8% in south basin for the same loading reductions. The north basin lower sediments responded minimally to reductions in loading by decreases in concentrations of 5 to 10%. However, in south basin, lower sediment Hg concentrations increased irrespective of reductions in loadings, governed principally by Hg introduction from deep, buried sediments. The Hg-rich buried sediment source term dampens the response of Hg concentrations in upper sediments and water column of south and middle basins.

To assess the effect of buried sediment introduction, the USS model was run with no introduction of Hg-rich deep sediments and Carson River load of 400 kg/yr (90% reduction). The model estimates a steady reduction in south basin water column concentrations from 800 ng/L to 350 ng/L over 10 years (Figure 6.15). Thus, sediment introduction term should be improved to improve model performance. In reality, the Carson River loadings and introduction of Hg-rich sediment both are declining with time.
Figure 6.15: Estimated response of the Lahontan Reservoir north basin to reduction in the Carson River loadings by 50 and 90%.

Legend: base, 50%, 90%
Figure 6.16: Estimated response of the Lahontan Reservoir south basin to reduction in the Carson River loadings by 50 and 90% and to reductions in loadings by 90% and no buried sediment introduction.
will witness an increase in both water column and sediment concentrations.

The introduction of Hg-rich sediments to the lower sediment layer is a calibrated term and Hg dynamics are strongly related to this term. To understand this relationship, the model was used to estimate Hg concentration in water column in south basin for reductions in the deep sediment introduction term by 5, 10, 20, 30, 50, and 100% (no introduction), with the Carson River loadings maintained at present levels. For no source introduction (100%), i.e. in-place pollutant is not being remobilised and no upward reworking occurs, the response is a uniform increase in sediment concentrations, controlled by net retention from Hg input, exports and burial, similar to most natural systems. As seen in Figure 6.16, the Hg concentration in the water column of south basin increases from 1100 ng/L to 1700 ng/L for 5% linear reduction in buried sediment concentrations, however, Hg concentration in water column increase to only 1260 ng/L for 50% linear reduction in buried sediment concentrations after 10 years. This indicates that the basin water concentrations will decline over time if buried sediments do not act as in-place pollutants. Further studies are required to understand this and perhaps, the deep sediments should be incorporated into the model as a compartment.

As stated earlier, in reality, the reservoir outlet water is controlled by dam operations. The USS model was used to evaluate the impact of dam operation by varying the outflow from the reservoir. North basin Hg concentrations in water column and sediments were estimated by doubling and halving the outflow from the reservoir. It was observed that water column and upper sediment concentrations are highly sensitive to dam operations (Figure 6.18). The water column Hg concentrations increase from 500 to 780 ng/L over ten years when the outflow is halved and decreases to 365 ng/L when outflow is doubled. Similarly, upper sediment concentrations increase from 6000 to 7700 ng/g and decrease to 4500 ng/g on halving and doubling the outflow, respectively. The outflow from the dam is regulated based on irrigation needs and is highest during summer. Truckee Canal flow is adjusted to keep constant water levels in north basin and hence is also highest during
concentration due to evaporation, that was not considered in the model. The effect of varying Truckee Canal flow was also estimated by halving and doubling the Truckee Canal flow and it was found that there was only 10% variation in Hg concentration in water and sediment (Figure 6.19) in north basin, recipient of canal inputs. Thus, changes in Truckee Canal inputs do not affect model results significantly.

Figure 6.17: Response of water column Hg concentration of south basin to linear reduction in Hg concentration of buried sediments as estimated by the USS model.
Figure 6.18: Estimated response of Hg concentration in north basin to changes to Dam Outflow.
Figure 6.19: Estimated response of Hg concentration in north basin to changes in Truckee Canal flow.
In general, the unsteady-state model results confirm that reservoir Hg dynamics are strongly influenced by the particle transport rates and that the south basin retains most of the Hg bearing particles. Over time, these particles are remobilised and move from south towards north basin. This implies increasing Hg concentrations in middle and especially north basin. It is observed that seasonal variations of loadings do not influence significantly the overall picture of the reservoir acting as Hg repository with the Hg bearing particles being retained in the sediments. The results indicate that accurate long term projections of Hg dynamics are difficult to formulate because 1) the large seasonal variations in reservoir dimensions and water flows; 2) the hypothesis of in-place Hg pollutant remobilisation from deep buried sediments; 3) outflow regulation by dam operations; 4) changes to loadings in the long run. Reservoir dimensions are controlled by inflows from Carson River and Truckee Canal, and losses due to evaporation. The basin dimensions are derived since no data is available to characterise the basin areas and volumes seasonally. Evaporation losses may or may not be significant. As seen earlier, remobilisation of Hg-rich sediments contribute significantly to sediment and water column Hg concentrations. Retention of Hg is an effect of the Lahontan Dam in the north end and reservoir operation characteristics. Better characterisation of these uncertainties is necessary for improving model estimations.
7. Conclusions and Recommendations

7.1 Hg dynamics - an overview

The three steady-state models and the integrated unsteady-state model have helped form the overall picture of the Hg dynamics in the Lahontan Reservoir. The reservoir receives varying water inflow through the Carson River and additionally, about 40% from Truckee Canal. The Carson River flows, which are well characterized, bring particle-bound Hg to the south basin. Most of the Hg bearing particles are deposited in the south basin. The exported Hg flows into the middle basin and finally to the north basin. The ‘cleaner’ particles from the Truckee Canal flows into the north basin and some of this flows back into the middle basin. Overall, approximately 90% of Hg is retained in the reservoir. Wind-driven turbulence in the shallow middle and south basin results in high resuspension rates that reintroduce and rework deposited sediments. South and middle basins dry during late summer. It is hypothesised that Hg-rich buried sediments, through a ‘shrink and swell’ process (Miller et al. 1995), mix with surficial sediments and enter the water column through resuspension. Particle transport dominates Hg movement within the reservoir.

Hg dynamics in the Lahontan Reservoir is in contrast with other polluted and remote systems due to the type of Hg present in the system. Most other Hg polluted systems studied (e.g., Parks et al. 1989; Bloom and Effler 1990) have Hg present as Hg(II) that can be converted to MeHg or Hg⁰, due to abiotic and biotic reactions. In the Lahontan Reservoir, Lechler et al. (1994) have suggested that the most abundant Hg species in the system is probably an amalgam with Au or Ag or Hg sulfide, rendering it unavailable for reaction/exchange mechanisms. MeHg in the Lahontan Reservoir is only 0.3% of total Hg whereas in other systems it is as high as 10% (Table 2.1). The results presented here have not indicated net MeHg production in the Reservoir. As discussed in Section 6.1, the availability of HgII for interconversion is probably the limiting factor controlling MeHg concentrations in the reservoir.
low water levels and Hg-rich sediments. Oremland et al. (1995) have reported that sediments in the Carson River system have the ability to methylate inorganic Hg. It is believed that this shallow bay offers favorable conditions for methylation i.e. flooded terrestrial area, warmer temperatures during summer, Hg remobilization from buried sediments, and probably benthos (Rudd et al. 1995; Miller et al. 1995; Furutani and Rudd 1980). However, the modeling results do not indicate net production of MeHg in the reservoir. This needs further investigation in the light of the above literature.

Dynamics in the reservoir differ significantly from other aquatic systems with deep basins in which sediments act as an ‘ultimate’ sink. In these systems, the resuspension of buried sediments is minimal and chemical can re-enter in water column through diffusion which is a slow process. In the Lahontan Reservoir, it is suggested that the historical repository of Hg in the sediments is remobilised by sediment mixing and resuspension. Thus the sediments are not an effective sink. As sedimentary Hg is remobilised from the south and middle basins, it is expected that the sediment concentrations in north basin will rise to a concentration dependent on Carson River loadings and to a lesser extent, dilution from the Truckee Canal. Hg is likely to be buried in the north basin, due to its consistently high water levels. In the long-term, the north basin may be the ‘ultimate’ sink of Hg bearing particles. However, Hg will remain for decades in the reservoir as export from the reservoir is minimal.

The major insights gained from this study are:

- Hg is predominantly associated with particles. These particles are mobilised from south to north basin. The reservoir acts as a particle trap and the retention of particles is controlled by dam operations.
- Hg mineralogy is not clearly understood, but it occurs in an unreactive form that does not appreciably undergo conversion to MeHg or Hg$^{\text{+}}$.
- Truckee Canal contributes about 40% of annual water requirements into the north basin but has minimal effect on Hg concentration.
Based on the above, following remedial options emerge:

- Truckee Canal, used presently to meet partial needs of irrigation, could be diverted to the Carson River outlet and not introduced into the reservoir. This ensures water with low Hg is available for irrigation at least for part of the year and the pollutant is not transported out of the system.

- Close the dam and let the dam overflow into the Carson River outlet. Additionally, build resistance to water flow, dropping velocities near the dam, to minimise particle export.

- Hg, associated with fine particles, is likely to remain suspended for prolonged periods prior to settling in the water column. North basin can be compartmentalised and systems instituted to agglomerate particles, and consequently increase deposition rates. This will facilitate increased removal of particles from water.

- A smaller dam can be built at the end of south or middle basin and particles trapped and dredged. The problem relating to dredged material disposal needs investigation in addition to understanding the hydrodynamics of the river and reservoir for an ideal location for a second dam.

- Examine the possibility of dredging the sediments for recovering Hg, Au and Ag. This option requires studying the reservoir and sediment mineralogy, recovery options, economics and environmental problems like dredged material disposal, release during recovery, physical problems of handling.

The model gives insights into various processes for making informed decisions on remedial actions. There are many unanswered questions on the importance of the reservoir for irrigation purposes, as a recreation location and the commercial fishery. A decision on the future of the reservoir will involve evaluating economical, social, political and other implications, with technical understanding being just one of them.
7.2 Conclusions

The result from the steady- and unsteady-state models suggest the following:

- Most Hg in the water column and upper sediments in all the basins are derived from the Carson River. Inputs from atmospheric deposition and Truckee Canal are negligible.

- More than 90% of the Hg entering from the Carson River is retained in the sediments of the reservoir, with the remainder lost through exports.

- Hg losses through volatilization as Hg⁰ are minimal, being constrained by limited conversion of residual Hg to Hg⁰.

- The proportion of MeHg in the reservoir is low (0.3% of input from the Carson River). MeHg in the reservoir is accounted for by inputs from the Carson River.

- Model results suggest that sediment concentrations are not fully supported by known inputs. It was hypothesized that deep, buried sediments with elevated Hg concentrations are a source of Hg to the surface sediments, and to a lesser extent, water column. This Hg works its way up through physical mixing in the sediment bed and is introduced into the water column through resuspension. The source of Hg will diminish over time. There is high degree of uncertainty in this rate of reduction or long term contribution from this term.

- Long term projections suggest that water column and sediment concentrations may rise or remain stable depending on assumptions of loading, buried sediment introductions and export rates (controlled by dam operations).
Over the long term, model results suggest that Hg-bearing particles will move from the south to north basin which may act as the 'ultimate' sink of Hg.

- The steady-state model results are sensitive to Hg loadings, the concentration of suspended particles, and rates of particle movement, namely sediment deposition, resuspension, burial and mixing.

- The unsteady-state model results are sensitive to reservoir dimensions, water flow rates, initial basin concentrations, the concentration of Hg-rich buried sediments, and rates of particle movement. It is suggested that better characterization of year-to-year loadings and hydrodynamics of the reservoir would contribute significantly to reducing the uncertainty in model estimates.

- Remediation studies should focus on particle retention in the basins by dam control, providing cleaner water for irrigation by Truckee Canal diversion, and building additional traps in the reservoir for particle settling and recovering Hg along with Au and Ag from the sediments.

### 7.3 Recommendations

Based on this modeling exercise, the following recommendations are made for future work, as well as, for improving the model performance:

1. The models are limited by parameter uncertainty, particularly by those associated to sediment-water exchange processes. Specifically, the description of deposition, resuspension, burial, and sediment mixing as separate processes, is a gross oversimplification of the real system. Since the model is highly sensitive to the particle transport parameters, it is recommended to better characterise these processes.

2. The assumption of homogeneity in the individual compartments is compromised by the existence of pockets of high Hg concentrations in sediments (Miller et al. 1995). The
The model under- or over-estimates concentrations based on this spatial variability not accounted for in the model. The model also assumes that homogeneity exists in terms of solids distribution in the water body and that the solids concentration in the outlet is equal to that in the main water body. This has likely led to overestimation of solids loads at the outlets of basins. It is recommended that the reservoir be more extensively sampled to understand the particle dynamics.

3 The deep, buried Hg-rich sediment should be included as a separate compartment in the model in order to account for its depletion as a source over time. The ‘shrink and swell’ process suggested for remobilisation of deep, buried Hg-rich sediments needs further investigation.

4 The unsteady-state model would benefit from a larger data base specifically of Hg loadings, buried sediment introduction rates and the mechanism responsible, reservoir dimensions and the effect of evaporation. Future modeling efforts on this system would benefit from an additional three years of monthly transport and Hg data, to allow the model to be more reliably parametrised. It would afford better characterisation of seasonal and spatial variability under a broader range of conditions and ultimately improve the utility of the model for remedial purposes.


Controlling factors in surface sediments of the Carson River system, Nevada. Environmental Pollution. 92:281-287.


Appendices

Appendix A  Program Listing of Steady-State Model for Lahontan Reservoir, Nevada - May 1995 snapshot.  104

Appendix B  Program Listing of Unsteady-State Model for Lahontan Reservoir, Nevada  124
Program Listing of Steady-State Model for Lahontan Reservoir, Nevada - May 1995 snapshot

Program in Borland C++

```c
#include <stdio.h>
#include <math.h>

int count, count1, basin;
float R = 8.314;
float Area_Lake[3], Area_S_W[3], Dpth_SedU[3], Dpth_SedL[3], XYZ;
float Vol_Water[3], Vol_SedU[3], Vol_SedL[3];
float Rain, Evap, W_dep, D_dep, Resq, Resqt;
float Wflow_Rain[3], Wflow_Evap[3], Wflow_In[3], Wflow_Out[3], Truckee_In;
float Vfrac_Asol, Vfrac_Par[3], Prsty_SedU, Prsty_SedL, Conc_Par[3], Conc_Par_in, Vfrac_in;
float Dens_Water, Dens_Asol, Dens_Par, Dens_Sed_par;
float W_A_Trans, A_W_Trans, S_W_Trans, S_S_Trans;
float P_Deposit[3], Su_Resusp[3], Su_Burial[3], Sl_Burial[3], Su_Mix[3], Sl_Mix[3], Truck[3], Sl_B[3];
float Wet_Deposit[3], Dry_Deposit[3];
float M_Weight[4], Henry[4], Vap_Pres[4], Melt_Point[4], Temp;
float TempK, dummy1[3], dummy2[3], dummy5[3], dummy7[3], dumbA[3], dumbB[3], dumbC[3];
float Kt_Air_Wat[3], Kt_Par_Wat[3], Kt_SedU_Pwat[3], Kt_SedL_Pwat[3], Kt_Sed_P[3];
float K_Air_Wat[3][3], K_Par_Wat[3][3], K_SedU_Pwat[3][3], K_SedL_Pwat[3][3], K_Sed_P[3][3];
float D_Wat_In[3][3][3], D_Par_In[3][3][3], D_Wat_Out[3][3][3], D_Par_Out[3][3][3];
float Y[7][3], X[7][3], Z[7][3][3], Zt[3][7], Zb_Air[3], Zb_Water[3], ZbU_Sediment[3], ZbL_Sediment[3];
float Dt_Wat_In[3][3], D_Par_In[3][3], D_Wat_Out[3][3], D_Par_Out[3][3];
float D_Rain_Dissol[3][3][3], D_Wet_Dep[3][3][3], D_Dry_Dep[3][3][3];
float D_Rain_Dissol[3][3], D_Wet_Dep[3][3], D_Dry_Dep[3][3];
float D_Par_Dep[3][3][3], D_Resusp[3][3][3], D_SedU_Bur[3][3][3], D_MixL_U[3][3][3],
       D_MixU_L[3][3][3], D_SedL_Bur[3][3][3], D_Truck[3][3][3];
float Dt_Par_Dep[3][3], D_Resusp[3][3], D_SedU_Bur[3][3], D_MixL_U[3][3],
       Dt_SedL_Bur[3][3], D_SedL_Back[3][3], D_MixL_U[3][3][3], D_Truck[3][3], TruckT[3][3][3];
float D_Volat[3][3][3], D_Absorp[3][3][3];
float D_Volat[3][3], D_Absorp[3][3];
float D_Wat_SedU_Diff[3][3][3], D_Wat_Wat_Diff[3][3][3];
float D_Wat_SedU_Diff[3][3], D_Wat_Wat_Diff[3][3];
float D_SedU_SedL_Diff[3][3][3], D_SedL_SedU_Diff[3][3][3];
float D_SedU_SedL_Diff[3][3], D_SedL_SedU_Diff[3][3];
float Conc_inflowW, Conc_inflowP, Load[3][3], Rain_Dissol[3][3], HgloadW, HgloadP, LoadP, LoadW;
float Aqui_air[3][3][3], Aqui_water[3][3][3], Aqui_sedU[3][3][3], Aqui_sedL[3][3][3],
       Aqui_sedU[3][3][3], Aqui_sedL[3][3][3], S_Aqui_sedU[3][3][3], Aqui_Init;
float Conc_water[3][3][3], Conc_water_dissol[3][3][3], Conc_water_part[3][3][3],
       Conc_part_inwater[3][3][3], Conc_sedU[3][3], Conc_sedU_solids[3][3][3],
       Conc_SedU_pw[3][3][3], Conc_sedL[3][3][3], Conc_sedL_solids[3][3][3],
       Conc_SedL_pw[3][3][3];
float Amt_water[3][3][3], Amt_water_dissol[3][3][3], Amt_water_part[3][3][3],
```
void output(void);

// Output File:
// Input File:
FILE *hgi;

hgi = fopen("inmaynew.hg", "r");

fscanf(hgi, "%f %f %f", &Area_Lake[0], &Area_Lake[1], &Area_Lake[2]);
fscanf(hgi, "%f %f %f", &Vol_Water[0], &Vol_Water[1], &Vol_Water[2]);
fscanf(hgi, "%f %f %f", &Dpth_SedU[0], &Dpth_SedU[1], &Dpth_SedU[2]);
fscanf(hgi, "%f %f %f", &Dpth_SedL[0], &Dpth_SedL[1], &Dpth_SedL[2]);
fscanf(hgi, "%f %f %f", &Pflow_In[0], &Trucke_In);
fscanf(hgi, "%f %f %f", &ConcPar[0], &ConcPar[1], &ConcPar[2]);
fscanf(hgi, "%f %f %f %f %f %f", &P_Deposit[0], &Su_Resusp[0], &Su_Burial[0], &SI_Burial[0], &Su_Mix[0], &SI_Mix[0], &SI_B[0]);
fscanf(hgi, "%f %f %f %f %f %f", &P_Deposit[1], &Su_Resusp[1], &Su_Burial[1], &SI_Burial[1], &Su_Mix[1], &SI_Mix[1], &SI_B[1]);
fscanf(hgi, "%f %f %f %f %f %f", &P_Deposit[2], &Su_Resusp[2], &Su_Burial[2], &SI_Burial[2], &Su_Mix[2], &SI_Mix[2], &SI_B[2]);
fscanf(hgi, "%f %f %f", &X[0][0], &X[0][1], &X[0][2]);
fscanf(hgi, "%f %f %f", &X[1][0], &X[1][1], &X[1][2]);
fscanf(hgi, "%f %f %f", &X[2][0], &X[2][1], &X[2][2]);
Rain    = 111;
Evap    = 1750;
    //W_dep = 1024 - scavenging ratio from fitzgerald et al,1991;
W_dep    = 1024;
    //D_dep = 0.5(cm/sec)/100*3600- m/h;
D_dep    = 18;
Dens_Water = 1.0;
Dens_Asol  = 2.0;
Dens_Par   = 2.4;
Dens_Sed_par = 2.4;
Vfrac_Asol    = 1.33E-11;
Prsty_SedU = 0.10;
Prsty_SedL = Prsty_SedU * 2;
Conc_Par_in    = 106.0;
Aqui_Init = 6.5E-06;
Conc_truckee = 46;

Area_S_W[0] = 0.80 * Area_Lake[0];
Area_S_W[1] = 0.65 * Area_Lake[1];
Area_S_W[2] = 0.60 * Area_Lake[2];

for ( count=0; count<3; ++count) {

Wflow_Rain[count] = Area_Lake[count] * Rain / (1000.0 * 365*24);
Wflow_Evap[count] = Area_Lake[count] * Evap / (1000.0 * 365*24);
Dry_Deposit[count] = Area_Lake[count] * D_dep * Vfrac_Asol;
Rain_Disol[count] = Wflow_Rain[count];
}

Wflow_Out[0] = Wflow_In[0] + Wflow_Rain[0] - Wflow_Evap[0];
Wflow_In[1] = Wflow_Out[0] + (0.2*Truckee_In);


for ( count=0; count<3; ++count) {

}
W_A_Trans = 1.0;
A_W_Trans = 0.01;
S_W_Trans = .0002;
S_S_Trans = 1E-08;

// Elemental Hg Properties
M_Weight[0] = 200.7;
Henry[0] = 488;
Vap_Pres[0] = .246;
Melt_Point[0] = -38.9;

// Residual Hg
// fscanf(hgi,"%f%f%f%f", &M_Weight[1], &Henry[1], &Vap_Pres[1], &Melt_Point[1]);
M_Weight[1] = 271.5;
Henry[1] = .001027;
Vap_Pres[1] = 0.0167;
Melt_Point[1] = 277;

// MeHg
// fscanf(hgi,"%f%f%f%f", &M_Weight[3], &Henry[3], &Vap_Pres[3], &Melt_Point[3] );
M_Weight[2] = 215.7;
Henry[2] = .03055;
Vap_Pres[2] = 1.76;
Melt_Point[2] = 167;

// fscanf (hgi, "%f", &Temp);
Temp = 20;
// 0=air 1=Aerosol 2=water 3=particulate 4=sediment 5=pore water
// 0=elemental labile 1=Residual 2=methyl mercury
// values of x for inlet stream:
X[6][0] = 5.17E-05;
X[6][1] = 0.9956;
X[6][2] = 0.0042;

TempK = Temp + 273.15;
for ( basin=0; basin<3; ++basin )
{
    for ( count=0; count<3; ++count )
    {
        Kt_SedL_Pwat[basin] = Kt_SedU_Pwat[basin] * 2.4;
        K_Air_Wat[basin][count] = Henry[count] / ( R * TempK );
        K_par_Wat[basin][count] = ( X[3][count] / X[2][count] ) * Kt_par_Wat[basin] * 2.4;
        K_sedU_Pwat[basin][count] = ( X[4][count] / X[5][count] ) * Kt_sedU_Pwat[basin] * 2.4;
        K_sedL_Pwat[basin][count] = ( X[4][count] / X[5][count] ) * Kt_sedL_Pwat[basin] * 2.4;
    }
}
for ( count=0; count<3; ++count)  {
    Z[basin][2][count] = 1.0;
    Z[basin][5][count] = 1.0;
    Z[basin][0][count] = K_Air_Wat[basin][count] / Z[basin][2][count];
    Z[basin][4][count] = K_SedU_Pwat[basin][count] / Z[basin][2][count];
    Z[basin][3][count] = K_Par_Wat[basin][count] / Z[basin][5][count];
    Z[basin][1][count] = (6.0E+06/(Vap_Pres[count]*exp(6.79*((Melt_Point[count] + 273.15) / TempK)))) * Z[basin][0][count];
    Z[basin][6][count] = K_Sed_P[basin][count] / Z[basin][2][count];
}
Z[basin][0][1] = 1.00E-14;
Z[basin][0][2] = 1.00E-14;
Z[basin][1][0] = (6.0E+6 / Vap_Pres[0]) * Z[basin][0][0];
Z[basin][1][2] = (6.0E+6 / Vap_Pres[0]) * Z[basin][0][2];
Zt[basin][2] = 1.0;
Zt[basin][5] = 1.0;
Zt[basin][0] = Kt_Air_Wat[basin]/Zt[basin][2];
Zt[basin][3] = Kt_Par_Wat[basin] * 2.4 / Zt[basin][2];
Zt[basin][4] = Kt_SedU_Pwat[basin] * 2.4 / Zt[basin][5];
Zt[basin][6] = Kt_Sed_P[basin] * 2.4 / Zt[basin][2];
Zb_Air[basin] = Zt[basin][0];

for (count =0; count<3; ++count)  {
    Zb_Water[count] = Zt[basin][3]*Vfrac_Par[count] + Zt[basin][2]*(1- Vfrac_Par[count]);
}

dummy[basin] = 0.0;
dummy3[basin] = 0.0;
dummy5[basin] = 0.0;
dummy7[basin] = 0.0;

for (basin=0; basin<3; ++basin) {
    for (count=0; count<3; ++count ){
        dummy[basin] += X[0][count] / Z[basin][0][count];
        dummy3[basin] += X[2][count] / Z[basin][2][count];
        dummy5[basin] += X[4][count] / Z[basin][4][count];
        dummy7[basin] += X[4][count] / Z[basin][6][count];
    }
}

for (basin=0; basin<3; ++basin) {
    for (count=0; count<3; ++count ){
        Y[0][count] = ( X[0][count] / Z[basin][0][count] ) / dummy[basin];
        Y[2][count] = ( X[2][count] / Z[basin][2][count] ) / dummy3[basin];
        Y[4][count] = ( X[4][count] / Z[basin][4][count] ) / dummy5[basin];
        Y[6][count] = ( X[3][count] / Z[basin][6][count] ) / dummy7[basin];
    }
}
LoadP = Conc_inflowP * Wflow_In[0] / (M_Weight[0] * 8760.0 * 1E+6);
LoadW = Conc_inflowW * Wflow_In[0] / (M_Weight[0] * 8760.0 * 1E+6);
Load[0] = LoadP + LoadW;

HgloadW = LoadW * 8760 * M_Weight[0];
HgloadP = LoadP * 8760 * M_Weight[0];

Dt_Truck[2] = Conc_truckee * Truckee_In/(M_Weight[0] * 8760.0 * 1E+6);
Dt_Truck[1] = 0.2 * Dt_Truck[2];
Dt_Truck[0] = 0.0;

Vfrac_in = Conc_Par_in / (Dens_Par * 1.E6);

// D values

for (basin=0; basin<3; ++basin)
{
    Dt_Wat_In[basin] = 0.0;
    Dt_Par_In[basin] = 0.0;
    Dt_Wat_Out[basin] = 0.0;
    Dt_Par_Out[basin] = 0.0;
    Dt_Rain_Dissol[basin] = 0.0;
    Dt_Wet_Dep[basin] = 0.0;
    Dt_Dry_Dep[basin] = 0.0;
    Dt_Par_Dep[basin] = 0.0;
    Dt_Resusp[basin] = 0.0;
    Dt_SedU_Bur[basin] = 0.0;
    Dt_MixL_U[basin] = 0.0;
    Dt_MixL_L[basin] = 0.0;
    Dt_SedL_Bur[basin] = 0.0;
    Dt_Volat[basin] = 0.0;
    Dt_Absorp[basin] = 0.0;
    Dt_Wat_SedU_Diff[basin] = 0.0;
    Dt_SedU_Wat_Diff[basin] = 0.0;
    Dt_SedU_SedL_Diff[basin] = 0.0;
    Dt_SedL_SedU_Diff[basin] = 0.0;
    Dt_SedL_Back[basin] = 0.0;

    Water_inT[basin] = 0;
    Part_inT[basin] = 0;
    Tot_InflowT[basin] = 0;
    Water_outT[basin] = 0;
    Part_outT[basin] = 0;
    Tot_OutflowT[basin] = 0;
    Net_DepositionT[basin] = 0;
    Sed_ResT[basin] = 0;
    Par_DepT[basin] = 0;
    SedU_BurialT[basin] = 0;
    NetD_A_WT[basin] = 0;
    Dif_water_airT[basin] = 0;
    Dif_air_waterT[basin] = 0;
    NetD_sedU_watT[basin] = 0;
Dif_water_sedUT[basin] = 0;
Net_MixL_UT[basin] = 0;
Mix_sedL_sedUT[basin] = 0;
Mix_sedU_sedLT[basin] = 0;
NetD_sedL_sedUT[basin] = 0;
Dif_sedL_sedUT[basin] = 0;
Dif_sedU_sedLT[basin] = 0;
SedL_BurialT[basin] = 0;
for (count=0; count<3; ++count)
{

D_Wat_In[basin][count] = (Wflow_In[basin] / 8760.0) * Z[basin][2][count];
Dt_Wat_In[basin] += Y[2][count] * D_Wat_In[basin][count];

D_Par_In[basin][count] = (Wflow_In[basin] * Vfrac_Par[basin-1] / 8760.0) * Z[basin][3][count];
D_Par_In[0][count] = (Wflow_In[0] * Vfrac_in / 8760.0) * Z[0][3][count];
Dt_Par_In[basin] += Y[2][count] * D_Par_In[basin][count];

D_Wat_Out[basin][count] = (Wflow_Out[basin] / 8760.0) * Z[basin][2][count];
Dt_Wat_Out[basin] += Y[2][count] * D_Wat_Out[basin][count];

D_Par_Out[basin][count] = (Wflow_Out[basin] * Vfrac_Par[basin] / 8760.0) * Z[basin][3][count];
Dt_Par_Out[basin] += Y[2][count] * D_Par_Out[basin][count];

D_Rain_Dissol[basin][count] = Rain_Dissol[basin] / 8760.0 * Z[basin][1][count];
Dt_Rain_Dissol[basin] += Y[0][count] * D_Rain_Dissol[basin][count];

D_Wet_Dep[basin][count] = Wet_Deposit[basin] / 8760.0 * Z[basin][1][count];
Dt_Wet_Dep[basin] += Y[0][count] * D_Wet_Dep[basin][count];

D_Dry_Dep[basin][count] = Dry_Deposit[basin] / 8760.0 * Z[basin][1][count];
Dt_Dry_Dep[basin] += Y[0][count] * D_Dry_Dep[basin][count];

D_Par_Dep[basin][count] = (P_Deposit[basin] * Area_S_W[basin]) / (Dens_Par * 24.0 * 1.0E6) * Z[basin][3][count];
Dt_Par_Dep[basin] += Y[2][count] * D_Par_Dep[basin][count];

D_Resusp[basin][count] = Su_Resusp[basin] * Area_S_W[basin] * Z[basin][4][count] / (Dens_Sed_par * 24.0 * 1.0E6);
Dt_Resusp[basin] += Y[4][count] * D_Resusp[basin][count];

(Dens_Sed_par * 24.0 * 1.0E6);
Dt_SedU_Bur[basin] += Y[4][count] * D_SedU_Bur[basin][count];

D_MixU_L[basin][count] = Su_Mix[basin] * Area_S_W[basin] * Z[basin][4][count] / (Dens_Sed_par * 24.0 * 1.0E6);
Dt_MixU_L[basin] += Y[4][count] * D_MixU_L[basin][count];
(Dens _Sed _par _* 24.0 _* 1.0E6);
Dt_MixL_U[basin] =+ Y[4][count] * D_MixL_U[basin][count];

D_SedL_Bur[basin][count] = S1_Burial[basin] * Area_S_W[basin] * Z[basin][4][count] /
(Dens _Sed _par _* 24.0 _* 1.0E6);
Dt_SedL_Bur[basin] =+ Y[4][count] * D_SedL_Bur[basin][count];

D_Volat[basin][count] = 1/(1/(W_A_Trans * Area_Lake[basin] * Z[basin][2][count]) +
1/(A_W_Trans * Area_Lake[basin] * Z[basin][0][count]));
Dt_Volat[basin] =+ Y[2][count] * D_Volat[basin][count];
D_Volat[basin][1] = 1.00E-14;

D_Absorp[basin][count] = 1/((1/W_A_Trans * Area_Lake[basin] * Z[basin][2][count]) +
1/(A_W_Trans * Area_Lake[basin] * Z[basin][0][count]));
Dt_Absorp[basin] =+ Y[0][count] * D_Absorp[basin][count];

D_Wat_Sedu_DifIbasin[count] = S_W_Trans * Area_S_W[basin] *
Z[basin][2][count];
Dt_Wat_Sedu_DifIbasin =+ Y[2][count] * D_Wat_Sedu_DifIbasin[count];

D_Sedu_Wat_DifIbasin[count] = S_W_Trans * Area_S_W[basin] *
Z[basin][2][count];
Dt_Sedu_Wat_DifIbasin =+ Y[4][count] * D_Sedu_Wat_DifIbasin[count];

D_SedL_SedU_DifIbasin[count] = S_S_Trans * Area_S_W[basin] *
Z[basin][5][count];
Dt_SedL_SedU_DifIbasin =+ Y[4][count] * D_SedL_SedU_DifIbasin[count];

D_SedL_Back[basin] = S1_B[basin] * Area_S_W[basin] * 6.5E04 / (M_Weight[0] *
24.0 _* 1.0E9);
}

// Compute equivalence values for air, water, sedL and sedU:

ZbU_Sediment[basin] = Zt[basin][4] _* Prsty_SedU + Zt[basin][5] _* (1 - Prsty_SedU);
ZbL_Sediment[basin] = Zt[basin][4] _* Prsty_SedL + Zt[basin][5] _* (1 - Prsty_SedL);

Aquai_air[basin] = 2.29E-09;

dumbA[basin] = (Dt_SedU_SedL_DifIbasin[count] + Dt_MixU_L[basin] +
Dt_SedU_Bur[basin] + Dt_Sedu_Wat_DifIbasin[count] + Dt_Resusp[basin]) -
((Dt_SedU_SedL_DifIbasin[count] + Dt_MixU_L[basin] + Dt_SedU_Bur[basin])
* (Dt_SedL_SedU_DifIbasin[count] + Dt_MixL_U[basin]) / (Dt_SedL_SedU_DifIbasin[count] +
Dt_MixL_U[basin] + Dt_SedL_Bur[basin]));

dumbB[basin] = (Dt_SedL_SedU_DifIbasin[count] + Dt_MixL_U[basin])*
Dt_SedL_Back[basin] / (Dt_SedL_SedU_DifIbasin[count] + Dt_MixL_U[basin] +
Dt_SedL_Bur[basin]);
dumbC[basin] = (Dt_Wat_Out[basin] + Dt_Par_Out[basin] + Dt_Wat_SedU_Diff[basin] + Dt_Par_Dep[basin] + Dt_Volat[basin]) / ((Dt_Wat_SedU_Diff[basin] + Dt_Par_Dep[basin]) / dumbA[basin]);

Aqui_water[basin] = (Load[basin] + ((Dt_Resusp[basin] + Dt_SedU_Wat_Diff[basin]) * dumbb[basin] / dumbA[basin]) + Dt_Truck[basin] + (Aqui_air[basin] * ((Dt_Absorp[basin] + Dt_Rain_Dissol[basin] + Dt_Wet_Dep[basin] + Dt_Dry_Dep[basin]))) / dumbC[basin];

Aqui_sedU[basin] = (Aqui_water[basin] * (Dt_Par_Dep[basin] + Dt_Wat_SedU_Diff[basin]) + ((Dt_SedL_SedU_Diff[basin] + Dt_MixL_U[basin]) * Dt_SedL_Back[basin]) / (Dt_SedL_SedU_Diff[basin] + Dt_MixL_U[basin] + Dt_SedL_Bur[basin])) / dumbA[basin];

Aqui_sedL[basin] = ((Aqui_sedU[basin] * (Dt_SedU_SedL_Diff[basin] + Dt_SedU_Bur[basin] + Dt_MixU_L[basin]) + Dt_SedL_Back[basin]) / (Dt_SedL_SedU_Diff[basin] + Dt_MixL_U[basin] + Dt_SedL_Bur[basin]));


//CALCULATIONS FOR RESULTS;

for (countl = 0; countl < 3; ++countl)
{
    Conc_water_dissol[basin][countl] = Aqui_water[basin] * Y[2][countl] * Z[basin][2][countl] * M_Weight[0] * 1.00e+06;
    TConc_water_dis[basin] += Conc_water_dissol[basin][countl];
}

Conc_water_part[basin][countl] = Aqui_water[basin] * Y[2][countl] * Z[basin][3][countl] * M_Weight[0] * Vfrac_Par[basin] * 1.00E+06; // ng/L;
    TConc_water_part[basin] += Conc_water_part[basin][countl];

Conc_water[basin][countl] = Conc_water_dissol[basin][countl] + Conc_water_part[basin][countl];
    Conc_water[basin] += Conc_water[basin][countl];

Conc_part_inwater[basin][countl] = Aqui_water[basin] * Z[basin][3][countl] * Vfrac_Par[basin] * M_Weight[0] * 1.00E+06; // ng/L;

Conc_sedU[basin][countl] = Y[4][countl] * (Aqui_sedU[basin] * (Z[basin][4][countl] * Prsty_SedU) + (Z[basin][5][countl] * (1 - Prsty_SedU)) * M_Weight[0] * 1.00E+03 / (Dens_Water * (1 - Prsty_SedU)) + (Dens_Sed_par * Prsty_SedU)); // ng/g bulk;
    TConc_sedU[basin] += Conc_sedU[basin][countl];
Z[p] + Z[4][p] * (1 - Prsty_SedL) + (Dens_Water * (1 - Prsty_SedL)) + (Dens_Sed_par * Prsty_SedL); // kg


// calculation of process/particle movement rates (g/y):


// calculation of process/particle movement rates (g/y):


Tot_inflow[basin] = Water_in[basin] + Part_in[basin];

Water_in[0][count1] = HgloadW * Y[2][count1];
Part_in[0][count1] = HgloadP * Y[2][count1];
Tot_Inflow[0][count1] = Water_in[0][count1] + Part_in[0][count1];
Water_inT[0] += Water_in[0][count1];
Part_inT[0] += Part_in[0][count1];
Tot_InflowT[0] += Tot_Inflow[0][count1];

TruckT[basin][count1] = Y[6][count1] * Dt_Truck[basin] * M_Weight[0] * 8760.0;
Dt_TruckT[basin] += TruckT[basin][count1];

Tot_Outflow[basin][count1] = Water_out[basin][count1] + Part_out[basin][count1];

Water_outT[basin] += Water_out[basin][count1];
Part_outT[basin] += Part_out[basin][count1];
Tot_OutflowT[basin] = Water_outT[basin] + Part_outT[basin];

//Sed transport terms:

Par_Dep[basin][count1] = Y[2][count1] * Aqui_water[basin] * D_Par_Dep[basin][count1] * M_Weight[0] * 8760.0;
Par_DepT[basin] += Par_Dep[basin][count1];

Sed_ResT[basin] += Sed_Res[basin][count1];

Net_Deposition[basin][count1] = Par_Dep[basin][count1] - Sed_Res[basin][count1];
Net_DepositionT[basin] = Par_DepT[basin] - Sed_ResT[basin];

SedU_Burial[basin][count1] = Y[4][count1] * Aqui_sedU[basin] * D_SedU_Bur[basin][count1] * M_Weight[0] * 8760.0;
SedU_BurialT[basin] += SedU_Burial[basin][count1];

//Diffusive Terms:

//air-water exchange term:

Dif_air_water[basin][count1] = Y[0][count1] * Aqui_air[basin] * D_Absorp[basin][count1] * M_Weight[0] * 8760.0;
Dif_air_waterT[basin] += Dif_air_water[basin][count1];

Dif_water_air[basin][count1] = Y[2][count1] * Aqui_water[basin] * D_Volat[basin][count1] * M_Weight[0] * 8760.0;
Dif_water_airT[basin] += Dif_water_air[basin][count1];

NetD_A_W[basin][count1] = Dif_air_water[basin][count1] - Dif_water_air[basin][count1];
Rain_Dissol[basin][count1] = D_Rain_Dissol[basin][count1] * 8760.0 * M_Weight[0] * Aqui_air[basin][Y[0][count1];
Rain_DissolT[basin] += Rain_Dissol[basin][count1];

Wet_Dep[basin][count1] = D_Wet_Dep[basin][count1] * 8760.0 * M_Weight[0] * Aqui_air[basin][Y[0][count1];
Wet_DepT[basin] += Wet_Dep[basin][count1];

Dry_Dep[basin][count1] = D_Dry_Dep[basin][count1] * 8760.0 * M_Weight[0] * Aqui_air[basin][Y[0][count1];
Dry_DepT[basin] += Dry_Dep[basin][count1];

// water-sedU exchange term;

Dif_water_sedU[basin][count1] = Y[2][count1] * Aqui_water[basin] * D_Wat_SedU_Diff[basin][count1] * M_Weight[0] * 8760.0;
Dif_water_sedUT[basin] += Dif_water_sedU[basin][count1];

Dif_sedU_water[basin][count1] = Y[4][count1] * Aqui_sedU[basin] * D_SedU_Wat_Diff[basin][count1] * M_Weight[0] * 8760.0;
Dif_sedU_waterT[basin] += Dif_sedU_water[basin][count1];

NetD_sedU_water[basin][count1] = Dif_sedU_water[basin][count1] - Dif_water_sedU[basin][count1];
NetD_sedU_waterT[basin] = Dif_sedU_waterT[basin] - Dif_water_sedUT[basin];

// sedU-SedL exchange terms;

Dif_sedU_sedL[basin][count1] = Y[4][count1] * Aqui_sedL[basin] * D_SedU_SedL_Diff[basin][count1] * M_Weight[0] * 8760.0;
Dif_sedU_sedLT[basin] += Dif_sedU_sedL[basin][count1];

Dif_sedL_sedU[basin][count1] = Y[4][count1] * Aqui_sedL[basin] * D_SedL_SedU_Diff[basin][count1] * M_Weight[0] * 8760.0;
Dif_sedL_sedUT[basin] += Dif_sedL_sedU[basin][count1];

NetD_sedL_sedU[basin][count1] = Dif_sedL_sedU[basin][count1] - Dif_sedU_sedL[basin][count1];
NetD_sedL_sedUT[basin] = Dif_sedL_sedUT[basin] - Dif_sedU_sedLT[basin];

SedL_BurialT[basin] += SedL_Burial[basin][count1];

Mix_sedU_sedL[basin][count1] = Y[4][count1] * Aqui_sedL[basin] * D_MixU_L[basin][count1] * M_Weight[0] * 8760.0;
Mix_sedU_sedLT[basin] += Mix_sedU_sedL[basin][count1];

Mix_sedL_sedU[basin][count1] = Y[4][count1] * Aqui_sedL[basin] * D_MixL_U[basin][count1] * M_Weight[0] * 8760.0;
Mix_sedL_sedUT[basin] += Mix_sedL_sedU[basin][count1];
Mix_sedU_sedL[basin][count1];
Net_MixL_UT[basin] = Mix_sedL_sedUT[basin] - Mix_sedU_sedLT[basin];

SedL_Back[basin][count1] = Dt_SedL_Back[basin] * 8760.0 * M_Weight[0] * X[4][count1];

if( basin<2)

Load[basin+1] = (Tot_OutflowT[basin] / (M_Weight[0] * 8760.0));
Water_in[basin+1][count1] = Water_out[basin][count1];
Part_in[basin+1][count1] = Part_out[basin][count1];
}

output()
{

void output(void)
{

FILE *hgo;
hgo = fopen( "outputnew.hg", "w" );
FILE *hgs;
hgs = fopen( "outputnew compilers.hgs", "w" );

Hgload[0] = (LoadP + LoadW)*8760*M_Weight[0];
Hgload[1] = Tot_OutflowT[0];
Hgload[2] = Tot_OutflowT[1];

for ( basin=0; basin<3; ++basin )
{
for ( count=0; count<3; ++count )
{

Input_water[basin] = (Hgload[basin] + Sed_ResT[basin] + Dif_air_waterT[basin] +
Dif_sedU_waterT[basin] + Rain_DissolT[basin] + Dry_DepT[basin] +
Df_TuckT[basin])/1000;

Output_water[basin] = (Tot_OutflowT[basin]+ Par_DepT[basin] + Dif_water_airT[basin] +
Dif_water_sedUT[basin])/1000;

Input_waterS[basin][count] = (Tot_Inflow[basin][count] + Sed_Res[basin][count] +
Dif_air_water[basin][count] + Dif_sedU_water[basin][count] + Rain_Dissol[basin][count] +
Dry_Dep[basin][count] + Wet_Dep[basin][count] + TruckT[basin][count])/1000;

Input_waterS[0][count] = ((Hgload[0]* X[6][count]) + Sed_Res[0][count] +
Dif_air_water[0][count] + Dif_sedU_water[0][count] + Rain_Dissol[0][count] +
Dry_Dep[0][count] + Wet_Dep[0][count] + Truck[0][count])/1000;

Output_waterS[basin][count] = (Tot_Outflow[basin][count]+ Par_Dep[basin][count] +
Dif_water_air[basin][count] + Dif_water_sedU[basin][count])/1000;
}
Input_sedU[basin] = (Dif_water_sedU[basin] + Par_DepT[basin] + Mix_sedL_sedU[basin] + Dif_sedL_sedU[basin])/1000;


Input_sedL[basin] = (Dif_sedU_sedLT[basin] + Mix_sedU_sedLT[basin] + SedU_BurialT[basin] + (D_t_SedL_Back[basin]*8760.0*M_Weight[0]))/1000;
Output_sedL[basin] = (Dif_sedL_sedUT[basin] + Mix_sedL_sedUT[basin] + SedL_BurialT[basin])/1000;

Input_sedLS[basin][count] = (Dif_sedU_sedLS[basin][count] + Mix_sedU_sedLS[basin][count] + SedU_BurialUS[basin][count] + SedL_Back[basin][count])/1000;

Input_waterX[0][count] = (Hgload[0]*X[6][count]); Input_waterX[1][count] = Tot_Outflow[0][count]; Input_waterX[2][count] = Tot_Outflow[1][count]; }
}

//print results;

fprintf (ligo, "Area_Lake[basin] : %1.3e, %1.3e, %1.3e:n", Area_Lake[0],Area_Lake[1], Area_Lake[2]);
fprintf (ligo, "Vol_Water[basin] : %10.3e, %10.3e, %10.3e:n", Vol_Water[0],Vol_Water[1], Vol_Water[2]);
fprintf (ligo, "Wflow_In[basin] : %10.3e, %10.3e, %10.3e:n", Wflow_In[0],Wflow_In[1], Wflow_In[2]);
fprintf (ligo,"Wflow_Out[basin] : %10.3e, %10.3e, %10.3e:n", Wflow_Out[0], Wflow_Out[1], Wflow_Out[2]);

fprintf (ligo, "Aqui_water[basin]: %10.3e, %10.3e, %10.3e:n", Aqui_water[0],Aqui_water[1], Aqui_water[2]);
fprintf (ligo, "Aqui_air[basin] : %10.3e, %10.3e, %10.3e:n", Aqui_air[0], Aqui_air[1], Aqui_air[2]);
fprintf (ligo, "Aqui_sedU[basin] : %10.3e, %10.3e, %10.3e:n", Aqui_sedU[0],Aqui_sedU[1], Aqui_sedU[2]);
fprintf (ligo, "Aqui_sedL[basin] : %10.3e, %10.3e, %10.3e:n", Aqui_sedL[0],Aquи_sedL[1], Aqui_sedL[2]);

fprintf(ligo," kg/y (\%) kg/y (\%) kg/y (\%):n");
fprintf(ligo,"Input_Water_Hg[basin] : %10.2e: %10.2e: %10.2e:n", Input_water[0], Input_water[1], Input_water[2]);
fprintf(ligo,"Tot_InflowT[basin] : %10.3e: %#2g%10.3e: %#2g%10.3e: %#2g:n", Hgload[0]/1000,(Hgload[0]/Input_water[0])/1E01);
fprintf(hgo,"Output_sedL_Hg[basin] : %10.2e: %10.2e: %10.2e\n",Output_sedL[0].
Output_sedL[1], Output_sedL[2]);
fprintf(hgo,"Dif_sedL_sedUT[basin] : %10.3e: %10.3e: %10.3e: %10.3e: %10.3e: %10.3e\n".
Dif_sedL_sedUT[0]/1000, (Dif_sedL_sedUT[1]/Output_sedL[0])/1E01,
Dif_sedL_sedUT[1]/1000, (Dif_sedL_sedUT[1]/Output_sedL[1])/1E01,
Dif_sedL_sedUT[2]/1000, (Dif_sedL_sedUT[2]/Output_sedL[2])/1E01);
fprintf(hgo,"Mix_sedL_sedUT[basin] : %10.3e: %10.3e: %10.3e: %10.3e: %10.3e: %10.3e\n".
Mix_sedL_sedUT[0]/1000, (Mix_sedL_sedUT[0]/Output_sedL[0])/1E01,
Mix_sedL_sedUT[1]/1000, (Mix_sedL_sedUT[1]/Output_sedL[1])/1E01,
Mix_sedL_sedUT[2]/1000, (Mix_sedL_sedUT[2]/Output_sedL[2])/1E01);
fprintf(hgo,"SedL_Burial[basin] : %10.3e: %10.3e: %10.3e: %10.3e: %10.3e: %10.3e\n".
SedL_Burial[0]/1000, ((SedL_Burial[0]/Output_sedL[0])/1E01),
SedL_Burial[1]/1000, ((SedL_Burial[1]/Output_sedL[1])/1E01),
SedL_Burial[2]/1000, ((SedL_Burial[2]/Output_sedL[2])/1E01));

for ( count=0; count<3; ++count )
{
if (count<1) fprintf(hgo, " Elemental Mercury data\n\n")
if (count==1) fprintf(hgo, " Inorganic Mercury data\n\n")
else if (count==2) fprintf(hgo, " Monomethyl Mercurydata\n\n")

fprintf(hgo,"","g/y (%) g/y (%) g/y (%)\n".
fprintf(hgo,"Input_Water[basin] : %10.3e: %10.3e: %10.3e\n",Input_waterS[0][count].
Input_waterS[1][count], Input_waterS[2][count]);
fprintf(hgo,"Tot_InflowT[basin] : %10.3e: %10.3e: %10.3e\n",(Hload[0]*X[6][count])/1000, Tot_Outflow[0][count], Tot_Outflow[1][count]);
fprintf(hgo,"Sed_ResT[basin] : %10.3e: %10.3e: %10.3e\n",Sed_Res[0][count], Sed_Res[1][count], Sed_Res[2][count]);
fprintf(hgo,"Dif_air_wat[basin] : %10.3e: %10.3e: %10.3e\n",Dif_air_water[0][count]/1000, Dif_air_water[1][count], Dif_air_water[2][count]);
fprintf(hgo,"Dif_sedL_waterT[basin] : %10.3e: %10.3e: %10.3e\n",Dif_sedL_water[0][count], Dif_sedL_water[1][count], Dif_sedL_water[2][count]);
fprintf(hgo,"Dif_sedU_waterT[basin] : %10.3e: %10.3e: %10.3e\n",Dif_sedU_water[0][count], Dif_sedU_water[1][count], Dif_sedU_water[2][count]);
fprintf(hgo,"Dif_TruckT[basin] : %10.3e: %10.3e: %10.3e\n",Dif_TruckT[0][count]/1000.
TruckT[1][count], TruckT[2][count]);
fprintf(hgo,"Atmos_LoadingT[basin] : %10.3e: %10.3e: %10.3e\n",(Rain_Dissol[0][count]+ Dry_Dep[0][count]+ Wet_Dep[0][count])/1000,
Dry_Dep[2][count]+ Wet_Dep[2][count]);

fprintf(hgo,"Output_Water_Hg[basin] : %10.3e: %10.3e: %10.3e\n",Output_waterS[0][count], Output_waterS[1][count], Output_waterS[2][count]);
fprintf(hgo,"Tot_OutflowT[basin] : %10.3e: %10.3e: %10.3e\n",Tot_Outflow[0][count]/1000, Tot_Outflow[1][count], Tot_Outflow[2][count]);
fprintf(hgo,"Par_DepT[basin] : %10.3e: %10.3e: %10.3e\n",Par_Dep[0][count]/1000, Par_Dep[1][count], Par_Dep[2][count]);
fprintf(hgo,"Dif\_water\_air\[0\][count]/1000,Dif\_water\_air\[1\][count], Dif\_water\_air\[2\][count]);
fprintf(hgo,"Dif\_water\_sedUT\[basin\]: %10.3e: %10.3e: %10.3e:\n".
Dif\_water\_sedU\[0\][count],Dif\_water\_sedU\[1\][count],Dif\_water\_sedU\[2\][count]);

fprintf(hgo,"Input\_sedU\_Hg\[basin\]: %10.3e: %10.3e: %10.3e:\n", Input\_sedUS\[0\][count], Input\_sedUS\[1\][count], Input\_sedUS\[2\][count]);
fprintf(hgo,"Dif\_water\_sedUT\[basin\]: %10.3e: %10.3e: %10.3e:\n".
Dif\_water\_sedU\[0\][count],Dif\_water\_sedU\[1\][count], Dif\_water\_sedU\[2\][count]);

fprintf(hgo,"Output\_sedU\_Hg\[basin\]: %10.3e: %10.3e: %10.3e:\n", Output\_sedUS\[0\][count], Output\_sedUS\[1\][count], Output\_sedUS\[2\][count]);
fprintf(hgo,"Dif\_water\_waterT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedU\_water\[0\][count],Dif\_sedU\_water\[1\][count], Dif\_sedU\_water\[2\][count]);
fprintf(hgo,"Sed\_Res\[T\][basin]\[count\]: %10.3e: %10.3e: %10.3e:\n", Sed\_Res\[0\][count], Sed\_Res\[1\][count], Sed\_Res\[2\][count]);
fprintf(hgo,"Mix\_sedU\_sedLT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Mix\_sedU\_sedL\[0\][count],Mix\_sedU\_sedL\[1\][count], Mix\_sedU\_sedL\[2\][count]);
fprintf(hgo,"Dif\_sedU\_sedLT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedU\_sedL\[0\][count],Dif\_sedU\_sedL\[1\][count], Dif\_sedU\_sedL\[2\][count]);
fprintf(hgo,"Sed\_U\_Burial\[T\][basin\]: %10.3e: %10.3e: %10.3e:\n", Sed\_U\_Burial\[0\][count],Sed\_U\_Burial\[1\][count],Sed\_U\_Burial\[2\][count]);

fprintf(hgo,"Input\_sedL\_Hg\[basin\]: %10.3e: %10.3e: %10.3e:\n", Input\_sedLS\[0\][count], Input\_sedLS\[1\][count], Input\_sedLS\[2\][count]);
fprintf(hgo,"Dif\_sedL\_sedLT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedL\_sedL\[0\][count],Dif\_sedL\_sedL\[1\][count], Dif\_sedL\_sedL\[2\][count]);
fprintf(hgo,"Mix\_sedL\_sedLT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Mix\_sedL\_sedL\[0\][count],Mix\_sedL\_sedL\[1\][count], Mix\_sedL\_sedL\[2\][count]);
fprintf(hgo,"Dif\_sedL\_sedLT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedL\_sedL\[0\][count],Dif\_sedL\_sedL\[1\][count], Dif\_sedL\_sedL\[2\][count]);
fprintf(hgo,"Sed\_L\_Back\[basin\]: %10.3e: %10.3e: %10.3e:\n", Sed\_L\_Back\[0\][count],Sed\_L\_Back\[1\][count],Sed\_L\_Back\[2\][count]);

fprintf(hgo,"Output\_sedL\_Hg\[basin\]: %10.3e: %10.3e: %10.3e:\n", Output\_sedLS\[0\][count], Output\_sedLS\[1\][count], Output\_sedLS\[2\][count]);
fprintf(hgo,"Dif\_sedL\_sedUT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedL\_sedU\[0\][count],Dif\_sedL\_sedU\[1\][count], Dif\_sedL\_sedU\[2\][count]);
fprintf(hgo,"Mix\_sedL\_sedUT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Mix\_sedL\_sedU\[0\][count],Mix\_sedL\_sedU\[1\][count], Mix\_sedL\_sedU\[2\][count]);
fprintf(hgo,"Dif\_sedL\_sedUT\[basin\]: %10.3e: %10.3e: %10.3e:\n", Dif\_sedL\_sedU\[0\][count],Dif\_sedL\_sedU\[1\][count], Dif\_sedL\_sedU\[2\][count]);
fprintf(hgo,"Sed\_L\_Burial\[T\][basin\]: %10.3e: %10.3e: %10.3e:\n", Sed\_L\_Burial\[0\][count],Sed\_L\_Burial\[1\][count],Sed\_L\_Burial\[2\][count]);

for ( basin=0; basin<3; ++basin )
{
if ( basin <1 ) fprintf(hgs, " South Basin data\n\n");
if ( basin==1 ) fprintf(hgs, " Middle Basin data\n\n");
fprintf(ligs, "Input_1basin : %10.3e: %10.3e: %10.3e: \n", Input_waterX[basin][0], Input_waterX[basin][1], Input_waterX[basin][2]);
fprintf(lgs, "Neteros_1basin : %10.3e: %10.3e: %10.3e: \n", TruckT[basin][0], TruckT[basin][1], TruckT[basin][2]);
fprintf(lgs, "Netinput_SedL%10.3e: %10.3e: %10.3e: \n", SedL_Bac[basin][0], SedL_Bac[basin][1], SedL_Bac[basin][2]);

fprintf(lgs, "Outflow_1basin : %10.3e: %10.3e: %10.3e: \n", Tot_Outflow[basin][0], Tot_Outflow[basin][1], Tot_Outflow[basin][2]);
fprintf(lgs, "SedL_Burial_1basin : %10.3e: %10.3e: %10.3e: \n", SedL_Burial[basin][0], SedL_Burial[basin][1], SedL_Burial[basin][2]);
fprintf(lgs, "NetVolat_1basin : %10.3e: %10.3e: %10.3e: \n", NetD_A_W[basin][0], NetD_A_W[basin][1], NetD_A_W[basin][2]);
fprintf(lgs, "Netlosses_1basin : %10.3e: %10.3e: %5.1e: \n", Tot_Outflow[basin][0]+SedL_Burial[basin][0]+NetD_A_W[basin][0], Tot_Outflow[basin][1]+SedL_Burial[basin][1]+NetD_A_W[basin][1], Tot_Outflow[basin][2]+SedL_Burial[basin][2]+NetD_A_W[basin][2]);

fprintf(lgs, "Int-species_Conv_1basin : %10.3e: %10.3e: %10.3e: \n", Tot_Outflow[basin][0]+SedL_Burial[basin][0]+NetD_A_W[basin][0]-Input_waterX[basin][0]-SedL_Bac[basin][0]-TruckT[basin][0], Tot_Outflow[basin][1]+SedL_Burial[basin][1]+NetD_A_W[basin][1]-Input_waterX[basin][1]-SedL_Bac[basin][1]-TruckT[basin][1], Tot_Outflow[basin][2]+SedL_Burial[basin][2]+NetD_A_W[basin][2]-Input_waterX[basin][2]-SedL_Bac[basin][2]-TruckT[basin][2]);
}
fclose (hgo);
return;
}

END
```
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.77E7</td>
<td>1.29E7</td>
<td>2.05E7</td>
</tr>
<tr>
<td>6.85E7</td>
<td>6.02E7</td>
<td>1.76E8</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>1.8163E09</td>
<td>3.288E08</td>
<td></td>
</tr>
<tr>
<td>22.8</td>
<td>21.0</td>
<td>21.4</td>
</tr>
</tbody>
</table>

// Lake areas

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6.85E7</td>
<td>6.02E7</td>
<td>1.76E8</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>1.8163E09</td>
<td>3.288E08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.8</td>
<td>21.0</td>
<td>21.4</td>
<td></td>
</tr>
</tbody>
</table>

// Water volumes

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>22.48</td>
<td>27.52</td>
<td>34.52</td>
</tr>
<tr>
<td>21.0</td>
<td>17.64</td>
<td>3.36</td>
<td>7.36</td>
</tr>
<tr>
<td>15.0</td>
<td>7.35</td>
<td>7.65</td>
<td>7.65</td>
</tr>
<tr>
<td>0.98</td>
<td>1E-12</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

// Dpth. sedL

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>22.48</td>
<td>27.52</td>
<td>34.52</td>
<td>5.0</td>
</tr>
<tr>
<td>21.0</td>
<td>17.64</td>
<td>3.36</td>
<td>7.36</td>
<td>3.0</td>
</tr>
<tr>
<td>15.0</td>
<td>7.35</td>
<td>7.65</td>
<td>7.65</td>
<td>0.1</td>
</tr>
</tbody>
</table>

// Dpth sedU

// Water flow- Carson, Truckee

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>22.48</td>
<td>27.52</td>
<td>34.52</td>
</tr>
<tr>
<td>21.0</td>
<td>17.64</td>
<td>3.36</td>
<td>7.36</td>
</tr>
<tr>
<td>15.0</td>
<td>7.35</td>
<td>7.65</td>
<td>7.65</td>
</tr>
<tr>
<td>0.98</td>
<td>1E-12</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>1E-12</td>
<td>0.97</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>0.003</td>
<td>0.967</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>1E-12</td>
<td>0.997</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>1E-12</td>
<td>0.9995</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>6.45E-5</td>
<td>0.91</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

// Conc. susp. part

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>5.06E5</td>
<td>5.49E5</td>
<td>1.09E3</td>
</tr>
<tr>
<td>0.005</td>
<td>5.90E5</td>
<td>3.02E5</td>
<td>1.74E3</td>
</tr>
<tr>
<td>0.005</td>
<td>5.06E5</td>
<td>1.76E5</td>
<td>9.06E2</td>
</tr>
</tbody>
</table>

// Conc. susp. part

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>1888</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

// Conc. susp. part

```

"Input the for May snapshot SS Model"
#include <stdio.h>
#include <math.h>
#include <float.h>

int basin, count, k, yr;
float t;
float R = 8.314;
float dt, LoadP, LoadW, Load[3], frac_sedU[3], frac_sedL[3];
double Vfrac_asol, Vfrac_par[3], Sed_prsty, SedL_prsty, Conc_par_in,
L_mix[3], U_mix[3],
Conc_par[3], Vfrac_par_in, denw, dens, denp, denq, WA_trans, AW_trans,
SW_diff, SS_diff, sed_back[3];
float MW[3], Henry[3], Vp[3], Mp[3], tempK, Ax[3], A[3], Ay[3];
float X[6][3], Y[6][3], Z[3][7][3], Zt[3][7], Zba[3], Zbw[3], Zbsu[3], Zbsl[3];
float dummy1[3], dummy2[3], dummy3[3], dummy4[3], FacA[3], FacB[3], FacU[3],
FacV[3], FacX[3], FacY[3], FacZ[3], I1[3], I2[3], I3[3], I4[3], I5[3], I6[3];
float KAWT[3], KPWT[3], KSUT[3], KSLT[3], KSPT[3], kaw[3][3], kpw[3][3],
ksu[3][3], ksl[3][3], ksp[3][3];
float conc_inW, conc_inP;
float DIT[3], DXT[3], DJT[3], DYT[3], DMT[3], DQT[3], DCT[3], DVT[3], DAT[3],
DDT[3], DRT[3], DSWUT[3], DWSUT[3], DET[3], DBUT[3], DBLT[3],
DMLT[3], DMUT[3], DS_BACK[3], DSUT[3], DSLT[3], Dt_Truck[3];
float DI[3][3], DX[3][3], DJ[3][3], DY[3][3], DM[3][3], DQ[3][3], DC[3][3],
DV[3][3], DA[3][3], DD[3][3], DR[3][3], DSWU[3][3], DWSU[3][3], DE[3][3],
DBU[3][3], DBL[3][3], DML[3][3], DMU[3][3], DS_BACK[3][3], DSU[3][3],
DSL[3][3];
float Aw[3], Vw[3], Vw_initial[3], W_depth[3], As[3], SedU_depth, SedL_depth, Vsu[3],
Vsl[3], Vsu_initial[3], Vsl_initial[3], Xw[3], Xs[3], Xsu[3];
float Rain, Evap, Wdep, Ddep, Conc_truckee, Rainfall[3], Evaporation[3], Wdep_rate[3],
Ddep_rate[3];
float Water_in[3], Water_out[3];
float Qa, Qw[3], Qsu[3], Qsua[3], Qsl[3], Qi, Qsb, Qw_initial[3], Qsu_initial[3],
Qsl_initial[3];
float f, E[3], W, Dep[3], Res[3], Buru[3], Burl[3];
float Diswat_conc[3][3], Diswat_concT[3], Parwat_conc[3][3], Parwat_concT[3],
Tconc_water[3], SedUpw_conc[3][3], SedUpw_concT[3], SedUpar_conc[3][3],
SedUpar_concT[3], TsedU_conc[3], SedUpar_concT_initial[3], SedU_conc[3][3],
SedLpar_conc[3][3], SedLpar_concT[3], Amt_sedUpar[3], Amt_sedUpar_initial[3],
Amt_sedUpar_initial[3], Amt_sedLpar[3];
float Dif_sedU_sedL[3][3], Dif_sedL_sedU[3][3], NetD_sedL_sedU[3][3];
float SedL_Burial[3][3], Mix_sedU_sedL[3][3], Mix_sedL_sedU[3][3], Net_mixL_U[3][3],
Dif_water_sedU[3][3], Dif_sedU_water[3][3], NetD_sedU_water[3][3],
Dif_air_water[3][3], Dif_water_air[3][3], NetD_A_W[3][3], SedU_Burial[3][3],
float Water_outT[3], Part_outT[3], Tot_OutflowT[3], Water_inT[3], Part_inT[3], Tot_InflowT[3], Net_DepositionT[3], Sed_ResT[3], Par_DepT[3], SedU_BurialT[3], Dif_water_airT[3], Dif_air_waterT[3], NetD_A_WT[3], MixU_LeT[3], NetD_sedU_waterT[3], Dif_sedU_waterT[3], Dif_water_airT[3], Dif_air_waterT[3], NetD_A_WT[3], MixU_LeT[3], SedL_BurialT[3], Rain_DissolT[3], Dry_DepT[3], Wet_DepT[3], ut_ErosT[3], Rain_Dissol[3], Dry_Dep[3], W&-Dep[3], SedL_BackT[3];

//chemistry
float Cheingers_wat[3], Chem_pers-sedL[3], ChemqerssedU[3], Chemqers_net[3], Input_water[3], Output_water[3], Input_sedL[3], Output_sedL[3], Input_sedU[3], Output_sedU[3], Input_waterX[3], Truckee_in, Sb;

float TConc_water_dis[3], TConc_water_part[3], TConc_water[3], TConc_sedU[3], TConc_sedU_solids[3], TConc_sedU_pw[3], Conc_sedLT[3], TConc_sedL_solids[3], TConc_SedL_pw[3], Hgl[3], Dt_True[3];

main()
{

    void output(void);
    FILE*hgi;
    FILE*hgo;
    FILE*hgs;
    hgi = fopen("input.ex", "r");
    hgs = fopen("Finalspe.ex", "w");
    hgo = fopen("finalout.ex", "w");

    // to define input X conc in order of air, aerosols, water, particles, sediment, porewater in order of Hgo, HgR, meHg)
    fscanf(hgi, "%f%f%f%f", &X[0][0], &X[0][1], &X[0][2]);
    fscanf(hgi, "%f%f%f%f", &X[1][0], &X[1][1], &X[1][2]);
    fscanf(hgi, "%f%f%f%f", &X[2][0], &X[2][1], &X[2][2]);
    fscanf(hgi, "%f%f%f%f", &X[3][0], &X[3][1], &X[3][2]);
    fscanf(hgi, "%f%f%f%f", &X[4][0], &X[4][1], &X[4][2]);
    fscanf(hgi, "%f%f%f%f", &X[5][0], &X[5][1], &X[5][2]);

    // total partition coefficients
    fscanf(hgi, "%f%f%f%f", &KAWT[0], &KPTW[0], &KSUT[0], &KSPT[0]);
    fscanf(hgi, "%f%f%f%f", &KAWT[1], &KPTW[1], &KSUT[1], &KSPT[1]);
    fscanf(hgi, "%f%f%f%f", &KAWT[2], &KPTW[2], &KSUT[2], &KSPT[2]);

    // inflow Hg concentrations
    Conc_truckee = 46;
    Rain = 111;
    Evap = 10;
    Wdep = 1024;
denw = 1.0;
denq = 2.0;
denp = 2.4;
dens = 2.4;
Vfrac_asol = 1.33E-11;
SedU_prsty = 0.10;
SedL_prsty = 0.20;
SedU_depth = .15;
SedL_depth = .10;
tempK = 293.15;
L_mix[0] = 0.25;
U_mix[0] = 0.25;
L_mix[1] = 0.1;
U_mix[1] = 0.1;
L_mix[2] = 0.001;
U_mix[2] = 0.001;

// rate of mass transfer being used in the model//
WA_trans = 1.0;
AW_trans = 0.01;
SW_diff = 2E-06;
SS_diff = 1E-08;

// Hg species properties used in the model - 0-elHg; 2- meHg; 1- hgR//
MW[0] = 200.7;
Henry[0] = 488;
Vp[0] = 0.246;
Mp[0] = -38.9;
MW[2] = 215.7;
Henry[2] = 0.03055;
Vp[2] = 1.76;
Mp[2] = 167;
MW[1] = 271.5;
Henry[1] = 0.0001027;
Vp[1] = 0.0167;
Mp[1] = 277;

// Initial values used/ calibrated
Qa = 2.290E-09;
Qw_initial[0]= 2.725E-06;
Qsu_initial[0] = 2.847E-07;
Qsl_initial[0] = 2.847E-07;

Vw_initial[0] = 3.52E07;
Vsu_initial[0]= 5.67E05;
// Computing partition coefficients for species
for (basin = 0; basin < 3; ++basin)
{
    for (count = 0; count < 3; ++count)
    {
        kaw[basin][count] = Henry[count] / (R * tempK);
        kpw[basin][count] = (X[3][count] / X[2][count]) * KPWT[basin] * 2.4;
        ksu[basin][count] = (X[4][count] / X[5][count]) * KSUT[basin] * 2.4;
        ksl[basin][count] = (X[4][count] / X[5][count]) * KSUT[basin] * 2.4;
        ksp[basin][count] = (X[4][count] / X[5][count]) * KSPT[basin] * 2.4;
    }
    // computing Z values
    for (count = 0; count < 3; ++count)
    {
        Z[basin][2][count] = 1.0;
        Z[basin][5][count] = 1.0;
        Z[basin][0][count] = kaw[basin][count];
        Z[basin][4][count] = ksu[basin][count];
        Z[basin][6][count] = ksl[basin][count];
        Z[basin][3][count] = kpw[basin][count];
        Z[basin][1][count] = (6.06E06 / (Vp[count] * exp((6.79 * ((M[p][count] + 273.15) / tempK))))) * Z[basin][0][count];
    }
    Z[basin][0][1] = 1E-14;
    Z[basin][1][0] = (6.0E6 / Vp[0]) * Z[basin][0][0];
    Z[basin][1][2] = (6.0E6 / Vp[0]) * Z[basin][0][2];
}
Zt[basin][2] = 1.0;
Zt[basin][5] = 1.0;
Zt[basin][0] = KAWT[basin];
\[ Z_{t[\text{basin}][4]} = K_{SU[T[\text{basin}]*2.4}; \\
Z_{t[\text{basin}][6]} = K_{SU[T[\text{basin}]*2.4}; \\
Z_{ba[\text{basin}]} = Z_{t[\text{basin}][0];} \\
Z_{bw[\text{basin}]} = Z_{t[\text{basin}][3]} \times V_{frac\_par[\text{basin}]} + Z_{t[\text{basin}][2]} \times (1 - V_{frac\_par[\text{basin}]}) \\
Z_{bsu[\text{basin}]} = Z_{t[\text{basin}][4]} \times \text{SedU\_prsty} + Z_{t[\text{basin}][5]} \times (1 - \text{SedU\_prsty}) \\
Z_{bsl[\text{basin}]} = Z_{t[\text{basin}][6]} \times \text{SedL\_prsty} + Z_{t[\text{basin}][5]} \times (1 - \text{SedL\_prsty}) \\
\]

\[ \text{dummy1[basin]} = 0; \]
\[ \text{dummy2 [basin]} = 0; \]
\[ \text{dummy3[basin]} = 0; \]

```
for (count = 0; count < 3; ++count)
{
    \text{dummy1[basin]} += X[0][count]/Z[basin][0][count];
    \text{dummy2[basin]} += X[2][count];
    \text{dummy3[basin]} += X[4][count]/Z[basin][4][count];
    \text{dummy4[basin]} += X[4][count]/Z[basin][6][count];
}
```

```
for (count = 0; count < 3; ++count)
{
    \text{Y[0][count]} = (X[0][count]/Z[basin][0][count])/\text{dummy1[basin]};
    \text{Y[2][count]} = (X[2][count]/Z[basin][2][count])/\text{dummy2[basin]};
    \text{Y[4][count]} = (X[4][count]/Z[basin][4][count])/\text{dummy3[basin]};
}
```

```
// Loop Starts for yearly calculation
for (yr = 1; yr < 11; yr++) {

    // Introduced sediment term variations yearly
    Sb = 9.5E07 \times (1 - (0.05*(yr-1)));
    if (Sb>0)
        Qsb = Sb;
    else
        Qsb = 0;

    // Time dependent =ns to be used
    for (t = 1; t < 8760; t = t+dt)
    {

        // suspended part. conc.
        \text{Conc\_par\_in} = 52.7 - (0.0397187*t) + (1.46652E-05*t*t) - (1.12906E-09*t*t*t);
        \text{A}[0] = (90.7 + (0.0215278*t) - (8.38346E-06*t*t) + (6.58532E-10*t*t*t));
        \text{A}[1] = 75.0 + (0.0140987*t) - (6.51423E-06*t*t) + (5.4395E-10*t*t*t);
    }
```
// volume
f = 144897000+(56464.8*t)-(37.1877*t^2)+(0.0141575*t^3)-
(0.0000202043*t^4)+
(0.0000000197502*t^5);

//flow rate
if (t<80)
   W = 10;
else
   W = ((-1655)+(24*t)-(0.0251218*t^2)+(0.0000000194*t^3)-
(0.0000000105372*t^4)+(0.000000000378275*t^5));

for (basin=0; basin<3; ++basin)
   {  
      Conc_par[basin] = A[basin];
      
      /* Generating Reservoir Dimensions*/
      // write volume of water =n interms of t = hours)
      // Divide the volume into three basins based on ratio

      Vw[0] = fabs(f)*0.26 ;
      Vw[1] = fabs(f)*0.18;
      Vw[2] = fabs(f)*0.56;

      W_depth[0] = 3.76;
      W_depth[1] = 4.52;
      W_depth[2] = 8.39;

      Aw[basin] = Vw[basin]/W_depth[basin];

      As[0] = 0.80 * Aw[0];
      As[1] = 0.65 * Aw[1];
      As[2] = 0.60 * Aw[2];

      Vsu[basin] = As[basin] * SedU_depth;
      Vsl[basin] = As[basin] * SedL_depth;

      // Generating flow , rainfall , atmos dep. and evaporation rates
      Rainfall[basin] = Aw[basin]*Rain/(1000.0*365*24);
      Evaporation[basin] = Aw[basin]*Evap/(1000.0*365*24);

      Wdep_rate[basin] = Rainfall[basin]*Wdep*Vfrac_asol;
      Ddep_rate[basin] = Aw[basin]*Ddep*Vfrac_asol;

      //water flowrates : cubic m/hr
      Truckee_in = ((1.75E06 + (1.69441E05*t) - (14.4756*t*t) - (0.00044499999997674946)t*t))/8760;

      Water_in[0] = fabs(W);
Water_in[0] = Water_out[0] - Evaporation[0] + Rainfall[0];

Water_in[1] = Water_out[0] + (0.2 * Truckee_in);


Vfrac_par[basin] = Conc_par[basin] / (denp * 1E06);
Vfrac_par_in = Conc_par_in / (denp * 1.0E06);

// particle transport terms
Dep[basin] = 0.0;
Res[basin] = 0.0;
sed_back[basin] = 0.0;
Buru[basin] = 0.0;
Burl[basin] = 0.0;

Dep[0] = (30 + (0.0030039 * t) + (1.94073E-07 * t^2) - (5.71912E-11 * t^3 * t)) / 24;
Res[0] = (29 + (0.00411898 * t) + (1.69288E-06 * t^2) + (1.35911E-10 * t^3 * t)) / 24;
sed_back[0] = (0.22 - (0.000385472 * t) + (1.56273E-07 * t^2) - (1.24835E-11 * t^3 * t)) / 24;

Dep[1] = (25 + (0.0139107 * t) - (3.86342E-06 * t^2) + (2.56178E-10 * t^3 * t)) / 24;
Res[1] = (24.5 + (0.00113132 * t) - (9.09894E-07 * t^2) + (8.60084E-11 * t^3 * t)) / 24;
sed_back[1] = (1.43 - (0.000802357 * t) + (4.25833E-07 * t^2) - (3.69855E-11 * t^3 * t)) / 24;

Dep[2] = (20 + (0.0167183 * t) - (4.74669E-06 * t^2) + (3.19207E-10 * t^3 * t)) / 24;
Res[2] = (19.54 + (0.00677945 * t) - (2.7229E-06 * t^2) + (2.16758E-10 * t^3 * t)) / 24;  // */
sed_back[2] = 0;

Buru[basin] = (Dep[basin] - Res[basin]);
Burl[basin] = Buru[basin] + sed_back[basin];

// D values
DIT[basin] = 0;
DXT[basin] = 0;
DJT[basin] = 0;
DYT[basin] = 0;
DMT[basin] = 0;
DCT[basin] = 0;

DQT[basin] = 0;
DTV[basin] = 0;
DAT[basin] = 0;
DDT[basin] = 0;
DRT[basin] = 0;
DBUT[basin] = 0;
DBLT[basin] = 0;
DMLT[basin] = 0;
for (count = 0; count<3; ++count)
{
    DI[basin][count] = (Water_in[basin]) * Z[basin][2][count];
    DIT[basin] += Y[2][count] * DI[basin][count];

    DX[basin][count] = (Vfrac_par[basin] * Water_in[basin]) * Z[basin][3][count];
    DXT[basin] += Y[3][count] * DX[basin][count];

    DJ[basin][count] = (Water_out[basin]) * Z[basin][2][count];
    DJT[basin] += Y[2][count] * DJ[basin][count];

    DY[basin][count] = (Vfrac_par[basin] * Water_out[basin]) * Z[basin][3][count];
    DYT[basin] += Y[3][count] * DY[basin][count];

    DM[basin][count] = (Rainfall[basin]/8760) * Z[basin][1][count];
    DMT[basin] += Y[1][count] * DM[basin][count];

    DQ[basin][count] = (Wdep_rate[basin]/8760) * Z[basin][1][count];
    DQT[basin] += Y[1][count] * DQ[basin][count];

    DV[basin][count] = (1/(1/WA_trans*Aw[basin]*Z[basin][2][count]) +
                      1/(AW_trans*Aw[basin]*Z[basin][0][count]))/8760;
    DV[basin][1] = 1e-14;
    DVT[basin] += Y[2][count] * DV[basin][count];

    DA[basin][count] = (1/(1/WA_trans*Aw[basin]*Z[basin][2][count]) +
                      1/(AW_trans*Aw[basin]*Z[basin][0][count]))/8760;
    DAT[basin] += Y[0][count] * DA[basin][count];

    DD[basin][count] = ((Dep[basin]*As[basin])/(denp*1E06)) * Z[basin][3][count];
    DDT[basin] += Y[3][count] * DD[basin][count];

    DR[basin][count] = ((Res[basin]*As[basin])/(dens*1E06)) * Z[basin][4][count];
    DRT[basin] += Y[4][count] * DR[basin][count];

    DBU[basin][count] = ((Bur[basin]*As[basin])/(dens*1E06)) * Z[basin][4][count];
    DBUT[basin] += Y[4][count] * DBU[basin][count];
DSU[basin][count] = SS_diff * As[basin] * Z[basin][5][count];
DSUT[basin] += Y[2][count] * DWSU[basin][count];

DSL[basin][count] = SS_diff * As[basin] * Z[basin][5][count];
DSL[basin] += Y[2][count] * DSL[basin][count];

DML[basin][count] = (L_mix[basin] * As[basin] * Z[basin][4][count])/(dens*1E06);
DMLT[basin] += Y[4][count] * DML[basin][count];

DMU[basin][count] = (U_mix[basin] * As[basin] * Z[basin][4][count])/(dens*1E06);
DMUT[basin] += Y[4][count] * DMU[basin][count];

D_SWUT[basin][count] = SW_diff * As[basin] * Z[basin][5][count];
D_SWUT[basin] += Y[2][count] * DSWU[basin][count];

D_B [count] = ((B [basin] * As[basin])/(dens*1E06)) * Z[basin][4][count] * Z[basin][4][count];
D_B += Y[4][count] * DML[basin][count];

D_B [count] = ((B [basin] * As[basin])/(dens*1E06)) * Z[basin][4][count] * Z[basin][4][count];
D_B += Y[4][count] * DML[basin][count];

D_Sw [count] = Sw_diff * As[basin] * Z[basin][5][count];
D_Sw += Y[2][count] * DSWU[basin][count];

LoadP = conc_inP * Water_in[O]/(MW[O]*1E06);
LoadW = conc_inW * Water_in[O]/(MW[O]*1E06);
Load[O] = (LoadP + LoadW);

Load[O] = (LoadP + LoadW);

Load[O] = (LoadP + LoadW);

Load[O] = (LoadP + LoadW);
I6[basin] = (DRT[basin]+DSWUT[basin]+DBUT[basin]+DMUT[basin]+DSUT[basin]) / Zbsl[basin];

FacB[basin] = (DBUT[basin]+DMUT[basin]+DSUT[basin])/Zbsl[basin];
FacA[basin] = (DBLT[basin]+DMLT[basin]+DSL[basin])/Zbsl[basin];

FacX[basin] = (2*Vsl[basin])*Vsl_initial[basin]+(FacA[basin]*dt);
FacY[basin] = (((DS_BACKT[basin]*dt)/Zbsl[basin]) + (Vsl[basin]*Qsl_initial[basin])/(FacX[basin]));
FacZ[basin] = ((15[basin]*dt*FacY[basin])/FacZ[basin] + Vsu[basin])/FacZ[basin];
FacV[basin] = (2*Vw[basin]) - Vw_initial[basin] + (I3[basin]*dt) - ((dt*I4[basin])*(I2[basin]*dt)/FacZ[basin]);

Qw[basin] = (((I1[basin]*dt)+(FacU[basin]*I2[basin]*dt)+(Qw_initial[basin]*Vw[basin]))/FacV[basin];
Qsu[basin] = (((I4[basin]*dt)*Qw[basin])/(FacZ[basin]) + FacU[basin];
Qsl[basin] = (((FacB[basin]*dt*Qsu[basin])/(FacX[basin])) + FacY[basin]);

Diswat_conc[basin][count] = 0.0;
Diswat_concT[basin] = 0.0;
Parwat_conc[basin][count] = 0.0;
Parwat_concT[basin] = 0.0;
SedUpar_conc[basin][count] = 0.0;
SedUpar_concT[basin] = 0.0;
SedLpar_conc[basin][count] = 0.0;
SedLpar_concT[basin] = 0.0;

Water_outT[basin] = 0.0;
Part_outT[basin] = 0.0;
Tot_OutflowT[basin] = 0.0;
Water_inT[basin] = 0.0;
Part_inT[basin] = 0.0;
Tot_InflowT[basin] = 0.0;
Sed_ResT[basin] = 0.0;
Par_DepT[basin] = 0.0;
SedU_BurialT[basin] = 0.0;
Dif_water_airT[basin] = 0.0;
Dif_air_waterT[basin] = 0.0;
Dif_sedU_waterT[basin] = 0.0;
Dif_water_sedUT[basin] = 0.0;
Mix_sedL_sedUT[basin] = 0.0;
Mix_sedU_sedLT[basin] = 0.0;
Dif_sedL_sedUT[basin] = 0.0;
Dif_sedU_sedLT[basin] = 0.0;
Rain_DissolT[basin] = 0.0;
Dry_DepT[basin] = 0.0;
Wet_DepT[basin] = 0.0;
SedL_BackT[basin] = 0.0;
//Calculations for Results;
for (count = 0; count < 3; ++count)
{
    // water concentration;
    Diswat_concT[basin] += Diswat_conc[basin][count];
    Parwat_conc[basin][count] = Qw[basin] * Y[2][count] * Z[basin][3][count] * MW[0] * 1E06 * Vfrac_par[basin];
    Parwat_concT[basin] += Parwat_conc[basin][count];
    Tconc_water[basin] = Diswat_concT[basin] + Parwat_concT[basin];

    // sedimentU concentration;
    SedUpar_conc[basin][count] = (Y[4][count] * Qsu[basin] * Z[basin][4][count] * MW[0] * 1E03) / dens;
    SedUpar_concT[basin] += SedUpar_conc[basin][count];
    SedUpar_concT_initial[basin] = (Y[4][count] * Qsu_initial[basin] * Z[basin][4][count] * MW[0] * 1E03) / dens;

    // sedimentL concentrations;
    SedLpar_concT[basin] += SedLpar_conc[basin][count];

    // amount of Sedu
    Amt_sedUpar_initial[basin] = SedUpar_concT[basin] * Vsu_initial[basin] * SedU_prsty * dens / 1.00E+03;
    Amt_sedUpar[basin] = SedUpar_concT[basin] * As[basin] * 5E-04 * SedU_prsty * dens / 1.00E+03;
    frac_sedU[basin] = Amt_sedUpar[basin] / (Amt_sedUpar[basin] + Amt_sedUpar_initial[basin]);

    // amount of Sedl
    Amt_sedLpar_initial[basin] = SedLpar_concT[basin] * Vsl_initial[basin] * SedL_prsty * dens / 1.00E+03;
    Amt_sedLpar[basin] = SedLpar_concT[basin] * As[basin] * 5E-04 * SedL_prsty * dens / 1.00E+03;
    frac_sedL[basin] = Amt_sedLpar[basin] / (Amt_sedLpar[basin] + Amt_sedLpar_initial[basin]);
    // calculation of process/particle movement rates (g/y);
    Water_outT[basin] = DJT[basin] * MW[0] * Qw[basin];
    Part_outT[basin] = DYT[basin] * MW[0] * Qw[basin];
Load[1] = Tot_OutflowT[0]/MW[0];
Load[2] = Tot_OutflowT[1]/MW[0];

Hgload[0] = Load[0]*MW[0];
Hgload[1] = Tot_OutflowT[0];
Hgload[2] = Tot_OutflowT[1];

//Sed transport terms;

Par_Dep[basin][count] = Y[2][count] * Qw[basin] * DD[basin][count] * MW[0];
Par_DepT[basin] += Par_Dep[basin][count];

Sed_Res[basin][count] = Y[4][count] * Qsu[basin] * DR[basin][count] * MW[0];
Sed_ResT[basin] += Sed_Res[basin][count];

Net_Deposition[basin][count] = Par_Dep[basin][count] - Sed_Res[basin][count];
Net_DepositionT[basin] = Par_DepT[basin] - Sed_ResT[basin];

SedU_Burial[basin][count] = Y[4][count] * Qsu[basin] * DBU[basin][count] * MW[0];
SedU_BurialT[basin] += SedU_Burial[basin][count];

SedL_Burial[basin][count] = Y[4][count] * Qsl[basin] * DBL[basin][count] * MW[0];
SedL_BurialT[basin] += SedL_Burial[basin][count];

//Diffusive terms;
//air-water exchange term;

Dif_air_water[basin][count] = Y[0][count] * Qa * DA[basin][count]* MW[0];
Dif_air_waterT[basin] += Dif_air_water[basin][count];

Dif_water_air[basin][count] = Y[2][count] * Qw[basin] * DV[basin][count] * MW[0];
Dif_water_airT[basin] += Dif_water_air[basin][count];

NetD_A_W[basin][count] = Dif_air_water[basin][count] - Dif_water_air[basin][count];
NetD_A_WT[basin] = Dif_air_waterT[basin] - Dif_water_airT[basin];

Rain_Dissol[basin][count] = DM[basin][count] * MW[0] * Qa* Y[0][count];
Rain_DissolT[basin] += Rain_Dissol[basin][count];

Wet_Dep[basin][count] = DQ[basin][count] * MW[0] * Qa * Y[0][count];
Wet_DepT[basin] += Wet_Dep[basin][count];

Dry_Dep[basin][count] = DC[basin][count] * MW[0] * Qa * Y[0][count];
Dry_DepT[basin] += Dry_Dep[basin][count];

// water-sedU exchange term;

Dif_water_sedU[basin][count] = Y[4][count]*Qw[basin]* DWSU[basin][count] * MW[0];
Dif_{sedU-sedU} [basin][count] = Y[4][count] * Qsu[basin] * DSU[basin][count] * MW[0];
Dif_{sedU-waterT} [basin] += Dif_{sedU-water} [basin][count];

NetD_{sedU-water} [basin][count] = Dif_{sedU-water} [basin][count] - Dif_{water-sedU} [basin][count];
NetD_{sedU-waterT} [basin] = Dif_{sedU-waterT} [basin] - Dif_{water-sedU} [basin];

// sedU-SedL exchange terms:

Dif_{sedU-sedL} [basin][count] = Y[4][count] * Qsu[basin] * DSU[basin][count] * MW[0];
Dif_{sedU-sedL-T} [basin] += Dif_{sedU-sedL} [basin][count];

NetD_{sedU-sedL} [basin][count] = Dif_{sedU-sedL} [basin][count] - Dif_{sedU-sedL} [basin][count];
NetD_{sedU-sedL-T} [basin] = Dif_{sedU-sedL-T} [basin] - Dif_{sedU-sedL}[count];

Mix_{sedU-sedL} [basin][count] = Y[4][count] * Qsu[basin] * DMU[basin][count] * MW[0];
Mix_{sedU-sedL-T} [basin] += Mix_{sedU-sedL} [basin][count];

NetMix_{L-UL} [basin][count] = Mix_{sedL-sedU} [basin][count] - Mix_{sedU-sedL}[count];
NetMix_{L-UL-T} [basin] = Mix_{sedL-sedU-T} [basin][count] - Mix_{sedU-sedL-T}[count];

SedL_BackT [basin] = DS_BACKT [basin] * MW[0]/1E03;
}
}

Qw_initial[0] = Qw[0];
Qw_initial[1] = Qw[1];
Qw_initial[2] = Qw[2];
Qsl_initial[0] = Qsl[0];
Qsl_initial[1] = Qsl[1];
Qsl_initial[2] = Qsl[2];
Qsu_initial[0] = Qsu[0];
Qsu_initial[1] = Qsu[1];
Qsu_initial[2] = Qsu[2];
Vw_initial[0] = Vw[0];
Vw_initial[1] = Vw[1];
Vw_initial[2] = Vw[2];
Vsu_initial[0] = Vsu[0];
\[ V_{su, initial}[2] = V_{su}[2] ; \]
\[ V_{sl, initial}[0] = V_{sl}[0] ; \]
\[ V_{sl, initial}[1] = V_{sl}[1] ; \]
\[ V_{sl, initial}[2] = V_{sl}[2] ; \]

if (k == 1) {
    fprintf(hgo, "%f %e %e %e\n", t, Tconc_water[0], SedUpar_conc[0][0] +
            SedUpar_conc[0][1] + SedUpar_conc[0][2], SedLpar_conc[0][0] +
            SedLpar_conc[0][1] + SedLpar_conc[0][2]);
}
if (k == 1) fprintf(hgo, "%f %e %e %e\n", t, Tconc_water[1], SedUpar_concT[1],
                        SedLpar_concT[1]);
if (k == 1) fprintf(hgo, "%f %e %e %e\n", t, Tconc_water[2], SedUpar_concT[2],
                        SedLpar_concT[2]);
}

//
if (k == 1) fprintf(hgo, "%f %e %e %e %e %e %e %e %e\n", t, Tconc_water[0], SedUpar_conc[0][0] +
                        SedUpar_conc[0][1] + SedUpar_conc[0][2], SedLpar_conc[0][0] +
                        SedLpar_conc[0][1] + SedLpar_conc[0][2], Tconc_water[1],
                        SedUpar_concT[1], SedLpar_concT[1],
                        Tconc_water[2], SedUpar_concT[2], SedLpar_concT[2]);

//
}
}

fprintf(hgo, "\n");
fclose(hgo);
}
END

Input file for USS Model (hgo)

0.98 1E-12 0.02 // conc fract - air - order Hg", HgR, MeHg
1E-12 0.97 0.03 // conc fract - aerosol
0.001 0.969 0.03 // conc fract - water
1E-12 0.9951 0.045 // conc fract - susp. part
1.74E-12 0.9993 0.0006 // conc fract - sed. part
1E-12 0.95 0.05 // conc fract - porewater
0.005 5.06E06 5.49E05 5.09E03 // part coeff - air, wat-part, sedu-pw, sedl [0]
0.005 1.11E06 3.21E05 6.10E03 // part coeff - air, wat-part, sedu-pw, sedl [1]
0.005 8.06E05 1.33E05 6.09E04 // part coeff - air, wat-part, sedu-pw, sedl [2]