UPDATE OF:

TECHNOLOGIES AND COSTS FOR THE REMOVAL OF RADIONUCLIDES FROM POTABLE WATER SUPPLIES

TARGETING AND ANALYSIS BRANCH
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OFFICE OF GROUND WATER AND DRINKING WATER
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LIST OF ACRONYMS

AA .... activated alumina
AWWA .... American Water Works Association
AX .... anion exchange

BLS .... Bureau of Labor Statistics
Bq .... Bequerel
BV .... bed volume

C/F .... coagulation/filtration
CFR .... Code of Federal Regulations
Ci .... curie
CX .... cation exchange

DF .... direct filtration

EBCT .... empty bed contact time
ED .... electrodialysis
EDR .... electrodialysis reversal
EDTA .... ethylenediaminetetracetic acid
ENR .... Engineering News Record
EPA .... United States Environmental Protection Agency

fCi .... femtocurie
ft .... feet

GAC .... granular activated carbon
gpd .... gallons per day
gpg .... grams per gallon
gpm .... gallons per minute

HDPE .... high-density polyethylene

ILF .... in-line filtration
IX .... ion exchange

kgal .... thousand gallons
kgpd .... thousand gallons per day
kWh .... kilowatt hour

LS .... lime softening

MCL .... Maximum Contaminant Level

MCLG .... Maximum Contaminant Level Goal
mg/L .... milligrams per liter
MGD or mgd ...... million gallons per day
MWCO .... molecular weight cut-off
MWDSC .... Metropolitan Water District of Southern California

NPDES .... National Pollutant Discharge Elimination System
NPDWR .... National Primary Drinking Water Regulation
NRC .... National Research Council
NTU .... nephelometric turbidity units

O&M .... operations and maintenance
OGWDW .... Office of Ground Water and Drinking Water

pCi .... picocurie
POE .... point-of-entry
POTW .... publicly-owned treatment works
POU .... point-of-use
ppb .... parts per billion
ppm .... parts per million
PPI .... Producer Price Index (for Finished Goods)
psi .... pounds per square inch
psig .... pounds per square inch gauge

rad .... radiation absorbed dose
RCRA .... Resource Conservation and Recovery Act
rem .... roentgen equivalent man
RIA .... Regulatory Impact Analysis
RO .... reverse osmosis

SDWA .... Safe Drinking Water Act
sf .... square feet
SI .... International System (of units)
sq ft .... square feet

TBLL .... Technically Based Local Limits
T&C .... Technologies and Costs
TCLP .... Toxicity Characteristic Leaching Procedure
TDP .... Technology Design Panel
TDS .... total dissolved solids
TOC .... total organic carbon
TSS .... total suspended solids

VSS .... Very small system

WET . . . . Whole Effluent Toxicity
wk . . . . week

yr . . . . year
μg/L . . . . micrograms per liter

EXECUTIVE SUMMARY

BACKGROUND AND PURPOSE

This document is an update of the United States Environmental Protection Agency (EPA) document, *Technologies and Costs for the Removal of Radionuclides from Potable Water Supplies* (EPA, 1999). Its purpose is to provide updated costs for applicable drinking water treatment technologies. These costs are needed to develop the national regulatory impact analysis (RIA) for radionuclide removals designed to meet proposed maximum contaminant levels (MCLs) of the proposed radionuclide regulation for drinking water, which is scheduled for promulgation in 2001.

This document includes summaries of various treatment options, the applicability of treatment techniques to the radionuclides of concern, and costs for the implementation of the treatment options. The radionuclides addressed here include:

- Radium-226 and-228
- Uranium-238, -235, and -234
- Polonium-210
- Lead-210
- Gross alpha particle activity, especially plutonium-239 and thorium-232
- Gross beta particle activity, in particular strontium-90, iodine-131, and tritium.

The radionuclide removal treatment technologies discussed in this document include:

- Coagulation/filtration, including direct filtration and in-line filtration
- Lime softening
- Ion exchange, including anion and cation exchange
- Reverse osmosis
- Electrodialysis reversal
- Greensand filtration
- Activated alumina.

Technologies applicable to point-of-entry (POE) and point-of-use (POU) treatment are also discussed.

1.0 INTRODUCTION

1.1 BACKGROUND AND PURPOSE

This document is an update of the United States Environmental Protection Agency (EPA) document, *Technologies and Costs for the Removal of Radionuclides from Potable Water Supplies* (EPA, 1999). The purpose of this document is to provide updated cost estimates for implementing water treatment technologies applicable to the removal of target radionuclides from drinking water. These cost estimates are needed to develop the national regulatory impact analysis (RIA) for radionuclide removals designed to meet proposed maximum contaminant levels (MCLs). The EPA is currently examining new proposed MCLs and national primary drinking water regulations (NPDWRs) for radium, uranium, gross alpha, and gross beta. The primary focus of the examination is to set the proposed MCLs as close as possible to the maximum contaminant level goals (MCLGs), taking into consideration both economical and technical factors. The proposed rule will reduce the level of public exposure to these various radionuclides by requiring that public water supply systems meet the MCLs shown in Table 1-1. It should be noted that the proposed MCLs listed below are subject to revision and may not represent the final regulatory levels. The final radionuclide rule is scheduled for promulgation in 2001.

Table 1-1
Proposed Radionuclide MCLs

CONTAMINANT	PROPOSED MCL
Radium-226	5 pCi/L
Radium-228	3, 2.5, 2, and 1 pCi/L
Radium-226/228 (combined)	5 pCi/L
Uranium	20 μg/L or 20 pCi/L
Gross Alpha radiation	15 pCi/L including Ra-226; 10 pCi/L excluding Ra-226
Gross Beta radiation	4 mrem per/ yr

The best available technologies (BATs) addressed in this document for removal of the target contaminants are shown in Table 1-2.

Table 1-2
Best Available Technologies Examined in This Document

PROCESS	APPLICABLE TO THE REMOVAL OF THE FOLLOWING							
	Ra	U	Pb	Po	ALPHA EMITTERS	BETA EMITTERS		
						STRONTIUM	TRITIUM	IODINE
Coagulation/Filtration - Direct Filtration - In-line Filtration		X X X	X			X*		X*
Lime Softening	X	X	X			X		
Anion Exchange		X		X				X
Cation Exchange	X	X				X		
Reverse Osmosis	X	X	X	X	X	X		X
Electrodialysis Reversal	X	X	X					
Greensand Filtration	X							
Activated Alumina		X						

Note: Ra - Radium, U - Uranium, Pb - Lead, Po - Polonium *-May require excessive coagulant dosages

This document includes updated costs for the implementation of various new treatment options, modifications to existing treatment systems, waste disposal alternatives, and land. In addition to the RIA, this document serves as a resource for public water systems in selecting economical and effective strategies to meet the radionuclides regulations. Prior to the implementation of any strategy, a site-specific engineering study should be performed to identify the most feasible technology application. The following factors should be considered in any site specific technical evaluation:

- Quality and type of water source;
- Degree of radionuclide contamination;
- Specific compound(s) present in water source;
- Economies of scale and the economic stability of the community being served;
- Treatment, waste disposal and land requirements.

1.2 DOCUMENT ORGANIZATION

This document is organized according to the following sections:

- **Chapter 2 - DESCRIPTION OF RADIONUCLIDES:** provides updated background information on the specific radionuclides.

- **Chapter 3 - DEVELOPMENT OF COSTS:** provides the basis for cost development including discussion of cost indices, amortization factors, and curve fitting analysis.

- **Chapters 4 through 11 - TECHNOLOGIES FOR RADIONUCLIDE REMOVAL:** provides a short summary including background information, process descriptions, and case studies as outlined in the 1999 and 1992 T&C documents, and any updated information. Also included in these sections are cost curves and equations for selected treatment technologies.

- **Chapter 12 - RESIDUALS HANDLING AND DISPOSAL OPTIONS:** provides background information, design criteria, and cost equations for the disposal options outlined in the technology sections, plus information and cost equations for additional disposal options.

- **Chapter 13 - REFERENCES:** provides the references used in the preparation of this addendum.

- **Appendices** - Includes supporting documentation used in the development of this Technology and Cost document.

BASIS FOR COST ESTIMATES

The three cost models used in this document for cost development include: the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993), hereafter referred to as the VSS model; the *Water Model* (Culp/Wesner/Culp, 1984); and the *W/W Cost Model* (Culp/Wesner/Culp, 1994). Curve fitting analysis was conducted on the modeled cost estimates, and included transition flow regions to provide better cost estimates within the breakpoints between the models. The following flow ranges were used:

- VSS - 0.015 to 0.100 mgd
- Transition 1 - 0.100 to 0.270 mgd
- Water Model - 0.27 to 1.00 mgd
- Transition 2 - 1 to 10 mgd
- W/W Cost Model - 10 to 200 mgd

Total capital costs consist of three elements: process, construction, and engineering costs. Process costs include manufactured equipment, concrete, steel, electrical and instrumentation, pipes and valves, and housing costs. Construction costs include sitework and excavation, standby power, land, contingencies, and interest during construction. Engineering costs include general contractor overhead and profit, engineering fees, and legal, fiscal, and administrative fees.

TREATMENT COSTS

The costs for implementing treatment technologies for the removal of radionuclides are based on design parameters published in the 1999 radionuclides T&C document (EPA, 1999), the 1992 radionuclides T&C document (EPA, 1992), the November 1999 arsenic T&C document, and assumptions provided in the cost models (i.e., VSS, WATER Model, and W/W Cost Model). In addition, assumptions were made regarding the feasibility of the various technologies for the removal of the target radionuclides, based on available published data. A maximum percent removal was assigned to each target radionuclide for each treatment technology, and estimated costs were developed for each radionuclide at this maximum percent removal. If a target radionuclide cannot be feasibly removed by a given technology, or if there is no published information on its removal feasibility, no cost estimate is made for that radionuclide using that technology.

In this document, costs are provided for:

- Enhanced coagulation: uranium, lead, beta emitters.
- Lime softening: radium, uranium, lead, beta emitters.
- Ion exchange: radium, uranium, polonium, alpha emitters, beta emitters.
- Reverse osmosis: radium, uranium, polonium, lead, alpha emitters, beta emitters.
- Greensand filtration: radium.

The following technologies were not costed, but are nonetheless discussed:

- Coagulation/filtration, including direct filtration, and in-line filtration.
- Enhanced lime softening.
- Electrodialysis reversal.
- Activated alumina.

POINT-OF-USE / POINT-OF-ENTRY

Centralized treatment is not always a feasible treatment option, for example, in areas where each home has a private well or where centralized treatment is cost prohibitive. In these instances, POE and POU treatment options may be acceptable treatment alternatives. These systems may also reduce engineering, legal, and other fees typically associated with centralized treatment options. This document discusses three applicable POU and POE treatment techniques for removal of radionuclides from drinking water:

- POU reverse osmosis for radium and uranium removal
- POU ion exchange for radium and uranium removal
- POE cation-exchange for radium removal.

RESIDUALS HANDLING AND DISPOSAL OPTIONS

Each of the treatment technologies presented in this document will produce residuals, either solid or liquid streams, containing elevated levels of radionuclides. The characteristics of this waste, and appropriate handling and disposal options, are discussed in this document. Capital and O&M

costs for residuals handling and disposal options are also presented, along with references which contain appropriate cost information, for determining costs for additional options.

A number of factors can influence capital and operations and maintenance (O&M) costs associated with residuals handling and disposal. The primary factor affecting capital cost is the amount of residuals produced, which is dependent upon the design capacity of the water treatment plant and the treatment process used. The amount of waste generated plays a significant role in determining the handling and disposal method to be utilized. Many residuals-handling methods which are suitable for smaller systems are impractical for larger systems because of the significant land requirements. For larger systems that process residuals on-site (as opposed to direct or indirect discharge), mechanical methods are typically used because of the limited land requirements.

Operations and maintenance costs for handling and disposal methods include labor, transportation, process materials and chemicals, and maintenance. Many handling and disposal methods require extensive oversight which can be a burden on small water systems. Generally, labor intensive technologies are more suitable to large water systems. Transportation can also play a significant role in determining appropriate handling and disposal options.

Residuals handling and disposal costs can be difficult to estimate. Two EPA manuals are recommended for estimating costs: (1) *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993a); and (2) *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b). Both present a variety of handling and disposal options, applications and limitations of those technologies, and capital and O&M cost equations.

2.0 DESCRIPTION OF RADIONUCLIDES

2.1 BACKGROUND

Radionuclides are elements which undergo spontaneous nuclear decay by emitting various forms of radiation energy, or "nuclear decay products." The occurrence of radionuclides in drinking water is a concern mostly because of the tissue damage that may occur in the human body as a result of exposure to this radiation energy, and the subsequent carcinogenic effects.

The 1992 T&C document (EPA, 1992) provides a description of the radionuclides of concern with regard to drinking water. Much of the descriptive information on radionuclides provided in this section is summarized from the 1992 T&C document.

Radionuclides generally fall into two broad categories: naturally occurring and man-made. Naturally occurring radionuclides, including uranium and radium, are common in crystalline rocks and are usually present mostly in ground water sources, but also can be found in surface waters. In contrast, man-made radionuclides are found mostly in surface waters. The most widespread delivery of man-made radionuclides to the environment occurred as a result of fallout from nuclear weapons testing. Man-made radionuclides also are released, either planned or inadvertently, from defense-related industrial activities; nuclear power plants; institutions such as hospitals, research foundations, and universities; and other commercial/industrial users of radioisotopes.

2.1.1 Radioactive Decay

The decay of radionuclides results in the release of a number of possible decay products, including alpha particles, beta radiation, gamma radiation, and fission products. Alpha particles are emitted during the transformation of the parent nucleus in the alpha decay process. Alpha particles have the same atomic number and atomic mass as a helium atom, consisting of two protons and two neutrons. Therefore, emission of an alpha particle produces a progeny atom which has an atomic number two less than that of the parent element (two less protons) and an atomic mass four less than the parent element (removal of two protons and two nuetrons). Alpha particles do not have a long range or high penetration ability, and therefore pose little harm by external exposure. However, when allowed to enter the body via ingestion, inhalation, or an open wound, alpha emitters potentially constitute a health threat, depending on the levels present.

Beta radiation is characterized by the emission of electrons from the nucleus. A neutron decays into a proton which remains in the nucleus, and an electron which is ejected as the beta particle. Neutron decay produces a daughter element whose atomic number is one greater that the parent element (because of the extra proton); the atomic weight of the element does not change. Energetic beta particles can pass through skin, however the primary hazard from beta radiation is internal deposition by ingestion or inhalation of beta emitters.

Gamma rays are high-energy photons which are released when the nucleus moves to a lower energy state. They are similar to ordinary X-rays, but are higher in energy. Gamma ray emission does not change the atomic number or weight of the parent element. Gamma rays are highly penetrating, and are able to irradiate the human body from an external source.

Fission occurs when an atomic nucleus is split into two approximately equal parts. Fission can occur spontaneously, or it may be induced by the capture of bombarding particles. In addition to the fission products, neutrons and gamma rays are usually emitted during fission.

2.1.2 Daughter Products

The natural radionuclides that are of most interest in drinking water are found within the decay series of uranium-238 (U-238), uranium-235 (U-235), and thorium-232 (Th-232). Because of its relative abundance and the longevity of many of its daughter products, the U-238 decay series is of primary concern in terms of health effects (Lowry et al., 1988). U-238, with a half-life of 4.5 billion years, begets a series of 13 linear radioactive decay products, as well as several secondary radionuclides. Each atom of U-238 undergoes a series of successive radioactive transformations which produce a total of eight alpha and six beta emissions before ultimately evolving into one nonradioactive stable isotope of lead-206 (Pb-206). Half-lives of the intermediate daughter products range from a few minutes to thousands of years. The more persistent products of decay are uranium-234 (U-234), radium-226 (Ra-226), radon-222 (Rn-222), polonium-210 (Po-210), and lead-210 (Pb-210), which are the U-238 daughter products that present the greatest health concerns in drinking water. Radium-228, a product of the Th-232 decay series, is also a potential health concern in drinking water, and is included in the discussions that follow.

2.1.3 Radionuclide Measurement

Contaminant concentrations in the environment are typically measured in terms of mass per unit volume, such as milligrams per liter (mg/L) or parts per million (ppm). However, the activity, rather than the mass, of a radionuclide causes its carcinogenic effect; therefore, units that define radiological activity are generally used for radionuclide measurements. The common units used to quantify radioactivity are: curie (Ci), picocurie (pCi), femtocurie (fCi), becquerel (Bq), rad, rem, and sievert (Sv).

The curie is equal to a nuclear transformation rate of 3.7×10^{10} disintegrations per second. One gram of radium has 1 Ci of activity (by definition), and one gram of U-238 has an activity of 3.6×10^{-7} Ci. A picocurie is equivalent to 10^{-12} Ci, and a femtocurie is 10^{-15} Ci. The International System (SI) units for activity is the becquerel, which is equivalent to one disintegration per second.

The effective dose of radioactivity also depends on the type of radiation, which is usually described as the dosage absorbed by tissue or matter. The rad (*r*adiation *a*bsorbed *d*ose) is the unit most commonly used to describe the absorbed dosage. One rad is equivalent to deposition of 100 ergs of energy in one gram of matter; 10 million ergs per second is equivalent to one watt of power.

Due to the difference in mass and charge, one rad of alpha particles does more damage than one rad of gamma rays. The rem, which is a unit of dosage equivalent (*r*oentgen *e*quivalent *m*an), reflects this additional impact. The rad and rem are related as follows:

$$\text{rem} = Q \times \text{rad}$$

Where:

Q = 1 for beta particles and all electromagnetic radiation (gamma rays and X-rays);

Q = 10 for neutrons from spontaneous fission, and protons;

Q = 20 for alpha particles and fission fragments.

The quality factor, Q, describes the relative harm caused by various types of radiation. The SI unit corresponding to the rem is the sievert; one Sv equals 100 rem.

2.2 SPECIFIC RADIONUCLIDES

The following radionuclides and decay products are addressed in this document:

- Radium-226 and Radium-228
- Uranium-238, -235, and -234
- Polonium-210
- Lead-210
- Gross Alpha Particle Activity
- Beta Particle Activity

Radium, uranium, alpha particle activity, and beta particle activity were addressed in the 1992 T&C document, and are summarized here from that document. Although Po-210 is a relatively short-lived isotope (half-life of 138 days) and is rarely a concern in most drinking water sources, it's occurrence in some ground waters warrants its special treatment here. Pb-210, a daughter product of the U-238 decay series, is also treated separately in this document because of its radioactive nature and the chemical toxicity of lead. Although radon is a concern in natural waters, it is addressed separately in a companion document prepared by EPA (*Technologies and Costs for the Removal of Radon from Drinking Water* - Draft, October 1998), and is not discussed here.

2.2.1 Radium-226 and -228

Radium-226 and -228 are decay products of the U-238 and Th-232 decay series, respectively. Because they occur naturally in a variety of rock types and have relatively long half-lives (1600 years for Ra-226 and 5.8 years for Ra-228), these isotopes are commonly found in ground waters.

Radium is the largest of the group IIA alkaline earth metals. Because of its size and its tendency to be a non-hydrolyzing divalent ion, radium is easily removed from ground water, especially when competing ions like calcium and barium are absent or in low concentrations. Radium also tends to form radium sulfate ($RaSO_4$), which is easily removed by adsorption (Clifford, 1990).

Several potential technologies are available for the effective removal of radium, as shown in Table 2-1. These include lime softening, ion exchange, reverse osmosis, electrodialysis reversal

(EDR), manganese dioxide adsorption/filtration, and radium selective complexers. Technologies and performance characteristics are discussed in detail in subsequent chapters.

Table 2-1

Applicable Technologies for Radium Removal

Treatment Method	Percent Removal[1]	Comments
Lime Softening	80-95	- Limited Studies - Highest removals at pHs > 10.6
Ion Exchange	90-99	- Cationic resins achieve best results - Disposal of regenerant waste is a problem due to radioactivity - Hardness may affect removals
Reverse Osmosis	90-99	- Pretreatment required - Higher removals at higher operating pressures
Electrodialysis Reversal [2]	>99	- Based on one study - Radium accumulates on stacks
MnO_2 Adsorption / Filtration [2]	80-95	- Presence of iron reduces removal percentages - Increase in hardness may reduce removals
Radium-Selective Complexers[2]	≈ 97	- Exhausted resins may be low radioactive waste - No longer commercially manufactured

(1) Removals as high as these ranges have been reported in the literature
(2) No costs have been developed for this method
(Source: 1992 T&C document)

2.2.2 Uranium-238, -235, and -234

Uranium-238, -235, and -234 are naturally occurring radionuclides. U-238 is the most abundant uranium isotope, constituting 99.3 percent of all uranium; U-235 (0.7 percent) and U-234 (0.005 percent) are relatively minor isotopes. Uranium enters ground water from bedrock, seepage from stockpiled mill tailings, mining activities, and disposal sites containing radioactive contamination. The primary health concern with uranium is its potential to cause cancer and kidney damage once ingested.

Enhanced coagulation/filtration can provide the required removals of uranium at relatively low costs. Ion exchange and reverse osmosis can also obtain high removals, but may be more applicable for small and medium-sized systems because of their high costs. Table 2-2 provides a summary of applicable technologies for uranium removal. Detail on these technologies is provided in subsequent chapters.

Table 2-2

Applicable Technologies for Uranium Removal

Treatment Method	Percent Removal (1)	Comments
Coagulation / Filtration	80-95	- Highest removals achieved at pHs 6 and 10. - Enhanced coagulation/filtration is a cost-effective alternative
Lime Softening (Large Systems Only)	85-99	- Limited Studies - Presence of magnesium may enhance or reduce removals depending on pH and concentration of Mg.
Ion Exchange	90-99	- Anion resins achieve highest percentage removals - Pre-filtration may be required - Regenerant waste may be low level radioactive
Reverse Osmosis	90-99	- Pretreatment required
Electrodialysis Reversal	>99	- Based on one study - Uranium accumulates on stacks
Activated Alumina	90-99	- Limited Studies - Limited Capacity

(1) Removals as high as these ranges have been reported in the literature
(Source: 1992 T&C document)

2.2.3 Polonium-210

Po-210 occurs in nature as a result of the radioactive decay of isotopes of the U-238 decay series. Po-210 has a half-life of 138 days, decaying through alpha emission to stable Pb-206. The isotope has been found in ground water in different parts of the country, though rarely at levels high enough to require treatment of the water. However, a statewide reconnaissance of radioactivity in water samples from domestic wells in Florida revealed several shallow wells in which the main contributor to high gross alpha activity was Po-210. Investigation of the distribution of Po-210 in ground water and the mechanisms of its mobilization suggests a possible association between high Po-210 activity and acidic waters containing sulfide (Harada et al., 1988). No instances of high Po-210 levels have been reported in surface waters.

2.2.4 Lead-210

Lead-210 is a naturally-occurring daughter product of the U-238 decay series. With a half-life of 21 years, a Pb-210 atom decays through two beta emissions to Po-210, which in turn decays to stable Pb-206. In addition to its radioactivity, Pb-210, like all isotopes of lead, is toxic to humans, accumulating in bone and tissue when ingested or inhaled. The major chronic effects of lead poisoning are produced in the hematopoietic system, the central and peripheral nervous systems, and the kidneys.

The most significant forms of lead in water are carbonate ($PbCO_3$), hydroxide ($Pb(OH)_2$), and hydroxycarbonate ($Pb_3(OH)_2(CO_3)_2$) forms. The carbonate form occurs in the pH range of 5 to 8, the hydroxide form occurs mostly above pH 8.5, and the hydroxycarbonate form is stable between pH 7.5 and 8.5. The hydroxycarbonate form occurs over so narrow a pH range that its significance in water treatment is minimal (Sorg and Logsdon, 1978).

Several investigations have studied lead removal from drinking water by conventional coagulation and lime softening. Alum and iron coagulation are very effective for lead removal because lead is easily adsorbed by turbidity and forms insoluble complexes in the normal pH range for coagulation treatment. In lime softening tests, greater than 99 percent removals of 0.15 mg/L of lead were achieved throughout the pH range 8.8 to 11.0 (Sorg and Logsdon, 1978). These and other treatment processes are discussed in detail in subsequent chapters.

2.2.5 Alpha Particle Activity

Most alpha-emitting radionuclides in water are naturally occurring. Since gross alpha particle activity is a measure of the total alpha emissions in a sample, different radionuclides, including those described above, can contribute to this activity. Therefore, if a specified gross alpha activity is exceeded in a drinking water, testing must be performed to identify the specific contaminants which are contributing to the activity. Table 2-3 provides characteristics of two additional alpha-emitting radionuclides, plutonium-239 and thorium-232, that may be of concern in some ground waters.

Table 2-3

Characteristics of Additional Alpha-Emitting Radionuclides

Parameter	Plutonium-239	Thorium-232
Half-life:	2.44 x 10E4 years	1.41 x 10E10 years
Principal Mode of Decay:	Alpha (100%)	Alpha (100%)
Sources:	Produced in thermal reactors by neutron irradiation of Uranium-238. Used in nuclear weapons and as fuel.	Naturally occurring
Special Chemical Characteristics:	Member of actinide series of rare-earth elements. Forms insoluble fluorides, hydroxides, and oxides. Forms soluble complexes with citrate.	Hydroxides and oxides are insoluble; nitrates, sulphates, chlorides, and perchlorate salts are readily soluble.
Critical Organs Affected:	Bone and lung	Bone and liver

(Source: Eisenbud, 1973)

2.2.6 Beta Radiation

Beta radiation is emitted during the radioactive decay of some naturally occurring and man-made radionuclides. Several daughter products of the U-238, U-235, and Th-232 decay series are beta emitters, although most are relatively short-lived. An exception is Pb-210 (half-life of 21 years) which is discussed in Section 2.2.4. Man-made radionuclides which emit beta particles include three that may be significant in some drinking waters: strontium-90 (Sr-90), iodine-131 (I-131), and tritium (T or H-3). Man-made radionuclides enter drinking water from nuclear weapons production and testing, nuclear power plant accidents and normal operational discharge, discharges from medical facilities, and leaching from radioactive waste facilities. Beta emitters affect mostly surface water because of their source from surface (i.e., human) activities.

Strontium-90

Sr-90 is a man-made radionuclide resulting from nuclear power generation, defense-related industrial activities, nuclear weapons testing, and natural fission of uranium nuclei. The isotope has a half-life of 29 years, decaying via beta emission to yttrium-90. Sr-90 has an affinity for bone marrow when ingested, resulting in increased risks of bone cancer and leukemia. Conventional coagulation alone is unsatisfactory for the removal of strontium from drinking water. To accomplish removals above 90 percent, iron coagulant doses of more than 500 mg/L at pH of 11 is required (Ciccone, 1987).

Iodine-131

I-131 is a man-made radionuclide resulting from nuclear fission in weapons and power plants. I-131 is also used in nuclear medicine applications, and can enter surface water supplies through contamination from hospital wastes. The isotope has a half-life of eight days, decaying to xenon-131 via beta emission. Iodine tends to concentrate in the thyroid gland when ingested, and the presence of radioactive iodine can cause thyroid disease, including cancer. Iodine is only slightly removed from drinking water by conventional alum or iron coagulation, but the addition of small amounts of copper sulfate, activated carbon, or silver nitrate has been shown to increase removal appreciably (EPA, 1986).

Tritium

Tritium is an isotope of hydrogen, containing one proton and two neutrons in the nucleus (i.e., hydrogen-3). The isotope has a half-life of 12.26 years, decaying to stable helium-3 through beta decay. Tritium is produced in nuclear reactors, and is used in the production of fusion nuclear weapons. Although minor amounts of tritium are produced naturally in the atmosphere from cosmic ray-induced nuclear reactions, most of the tritium contamination in drinking water is from atmospheric testing of nuclear weapons. Tritium is also used to make luminous paints and as a tracer element, and can enter the water cycle from these sources. Being chemically identical to hydrogen, tritium occurs in water as water molecules, making its removal from drinking water impractical by standard means.

3.0 DEVELOPMENT OF COSTS

3.1 INTRODUCTION

A primary objective of this document is to determine estimated costs for the removal of radionuclides from drinking water. The purposes of this chapter are to:

- Identify applicable removal technologies for each of the contaminants discussed in Chapter 2;
- Develop design criteria and assumptions associated with these alternatives; and
- Develop estimated capital and operations and maintenance (O&M) costs associated with each removal technology identified.

3.2 BASIS FOR COST ESTIMATES

3.2.1 Cost Modeling

The three cost models used in cost development include: the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993), hereafter referred to as the VSS model; the Water Model (Culp/Wesner/Culp, 1984); and the W/W Cost Model (Culp/Wesner/Culp, 1994). Curve fitting analysis was conducted on the modeled cost estimates including the utilization of transition flow regions to provide better estimates within the breakpoints between models. The following flow ranges have been established for each model and transition flow region:

- VSS - 0.015 to 0.100 mgd
- Transition 1 - 0.100 to 0.270 mgd
- Water Model - 0.27 to 1.00 mgd
- Transition 2 - 1 to 10 mgd
- W/W Cost Model - 10 to 200 mgd

All three models require flow to calculate direct capital and O&M costs. In addition to the flow, the Water and W/W Cost models require several other user-specified variables to generate direct capital cost. These additional user inputs include design factors, cost indices (Table 3-7), and other various unit costs (Table 3-8).

3.2.2 Technology Design Panel Recommendations

Since the 1986 Safe Drinking Water Act (SDWA) reauthorization, EPA has relied mainly on the previously mentioned unit cost models to estimate compliance costs for drinking water regulations. Following the reauthorization of the SDWA in 1996, EPA has critically evaluated its tools for estimating the costs and benefits of drinking water regulations. As part of this evaluation, EPA solicited technical input from national drinking water experts at the Denver Technology Workshop (which was sponsored by EPA and held November 6 and 7, 1997) to improve the quality of its compliance cost estimating process for various drinking water treatment technologies. The Technology Design Panel (TDP) formed at the workshop for this purpose recommended several modifications to existing cost models to improve the accuracy of EPA's compliance cost estimates.

The TDP developed guidelines for estimating capital costs using the three cost models. The guidelines are discussed in detail in *Guide for Implementing Phase I Water Treatment Upgrade* (EPA, 1998a) and *Water Treatment Costs Development (Phase I): Road Map to Cost Comparisons* (EPA, 1998b).

Total capital costs are comprised of three elements: process, construction, and engineering costs. Process costs include manufactured equipment, concrete, steel, electrical and instrumentation, pipes and valves, and housing costs. Construction costs include sitework and excavation, subsurface considerations, standby power, land, contingencies, and interest during construction. Engineering costs include general contractor overhead and profit, engineering fees, and legal, fiscal, and administrative fees (including permitting).

The TDP recommended that total capital cost estimates be generated based upon process costs. That is, the models can be used to estimate total capital costs, but process costs are then generated using the capital cost breakdowns presented in Appendices A through C of this document, and applying an appropriate factor for construction and engineering costs. These factors are based upon system size and are presented in Table 3-1.

Table 3-1

TDP Capital Cost Factors

System Size	Process Cost Factor (Percent of Total)	Construction Cost Factor (Percent of Total)	Engineering Cost Factor (Percent of Total)	Total Cost Factor[1] (Percent of Total)
Very Small	1.00 (40%)	1.00 (40%)	0.50 (20%)	2.50 (100%)
Small	1.00 (40%)	1.00 (40%)	0.50 (20%)	2.50 (100%)
Large	1.00 (30%)	1.33 (40%)	1.00 (30%)	3.33 (100%)

1 - This factor can be multiplied by the process cost to obtain the total capital cost.

Table 3-2 presents a sample capital cost breakdown for the VSS model membrane equations, i.e., microfiltration and ultrafiltration. The table also lists the capital costs assumptions associated with the VSS model. Capital cost breakdowns for all technologies costed using the VSS model are presented in Appendix A.

The Water and W/W Cost assumptions for capital cost components vary by design and average flow. This is due to changes in sizing requirements. Supporting documentation was used to develop capital cost breakdown summaries for the Water and W/W Cost models. *Estimation of Small System Water Treatment Costs* (Culp/Wesner/Culp, 1984) and *Estimating Treatment Costs, Volume 2: Cost Curves Applicable to 1 to 200 mgd Treatment Plants* (Culp/Wesner/Culp, 1979) were used for the Water and W/W Cost models, respectively. These documents present the design assumptions used in developing the cost models, as well as associated costs. The percent of total cost for each component cost was calculated for each design condition. These percentages were then averaged to arrive at a universal capital cost breakdown which could be applied for developing the Phase I capital costs. Tables 3-3 through 3-6 demonstrate the methodology described here.

Table 3-2

VSS Capital Cost Breakdown for

Membrane Processes (Including Microfiltration and Ultrafiltration)

Cost Component	Model Assumption	Cost Factor	Percent of Total Capital	Capital Cost Category
Manufactured Equipment	100%	1.000	56.97%	p
Installation	25%	0.2500	14.24%	c
Sitework and Interface Piping	6%	0.0750	4.27%	c
Standby Power	5%	0.0625	3.56%	c
General Contractor Overhead & Profit	12%	0.1665	9.49%	e
Legal, Fiscal and Administrative Fees	3%	0.0416	2.37%	e
Engineering	10%	0.1596	9.09%	e
Miscellaneous and Contingencies	0%	0.000	0.00%	c
TOTAL		1.7552	100.00%	

p = process, c = construction, e = engineering

Output from the Water and W/W Cost models includes construction costs and additional capital costs, which together make up the total capital cost. Additional capital costs include sitework and interface piping; standby power; overhead and profit; and engineering, legal, fiscal, and administrative fees. There are no process costs associated with the additional capital costs. As a result, cost breakdowns only need to consider the construction cost output from these two models. Tables 3-4 and 3-6 present sample capital cost breakdowns for the Water and W/W Cost models, respectively. Capital cost breakdowns for each technology and unit process are presented in Appendices A, B, and C for the VSS, Water, and W/W Cost models, respectively.

Table 3-3

Water Model Capital Cost Breakdown for Package Conventional Treatment (Coagulation/Filtration)

Cost Component	Filter Area (ft^2)						Capital Cost Category
	2	12	20	40	112	150	
Excavation and Sitework	$3,500	$3,500	$4,700	$5,800	$7,000	$9,300	c
Manufactured Equipment	$31,000	$44,900	$53,500	$111,300	$176,600	$190,500	p
Concrete	$1,000	$1,000	$1,500	$4,500	$5,700	$6,800	p
Labor	$9,900	$14,700	$17,500	$36,400	$57,800	$62,400	c
Pipes and Valves	$4,200	$8,300	$10,400	$20,900	$29,200	$41,700	p
Electrical	$3,200	$4,500	$5,300	$11,100	$17,600	$19,000	p
Housing	$18,600	$18,600	$23,400	$45,000	$47,500	$52,500	p
Subtotal	$71,400	$95,500	$116,300	$235,000	$341,400	$382,200	
Contingencies	$10,700	$14,300	$17,400	$35,300	$51,200	$57,300	e
Total	$82,100	$109,800	$133,700	$270,300	$392,600	$439,500	

Table 3-4

Water Model Capital Cost Breakdown by Percentage for Package Conventional Treatment (Coagulation/Filtration)

Cost Component	Filter Area (ft^2)						Average Percent
	2	12	20	40	112	150	
Excavation and Sitework	4.26%	3.19%	3.52%	2.15%	1.78%	2.12%	2.84%
Manufactured Equipment	37.76%	40.89%	40.01%	41.18%	44.98%	43.34%	41.36%
Concrete	1.22%	0.91%	1.12%	1.66%	1.45%	1.55%	1.32%
Labor	12.06%	13.39%	13.09%	13.47%	14.72%	14.20%	13.49%
Pipes and Valves	5.12%	7.56%	7.78%	7.73%	7.44%	9.49%	7.52%
Electrical	3.90%	4.10%	3.96%	4.11%	4.48%	4.32%	4.15%
Housing	22.66%	16.94%	17.50%	16.65%	12.10%	11.95%	16.30%
Contingencies	13.03%	13.02%	13.01%	13.06%	13.04%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table 3-5

W/W Cost Model Capital Cost Breakdown for Sedimentation Basins

Cost Component	Area ($A = ft^2$) and Length x Width (LW = ft x ft)						Capital Cost Category
	A=240 LW = 30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation and Sitework	$1,060	$2,000	$3,060	$4,680	$6,670	$8,090	c
Manufactured Equipment	$8,540	$12,080	$24,470	$32,020	$53,110	$63,440	p
Concrete	$2,970	$5,490	$84,430	$12,820	$19,190	$22,070	p
Steel	$6,400	$13,110	$19,440	$32,620	$51,250	$39,680	p
Labor	$6,220	$11,260	$17,320	$26,390	$37,570	$45,300	c
Pipes and Valves	$6,960	$7,400	$9,100	$12,500	$16,100	$21,450	p
Electrical	$1,510	$1,760	$1,860	$2,020	$2,110	$2,400	p
Subtotal	$33,660	$53,100	$83,680	$123,050	$190,000	$232,430	
Contingencies	$5,050	$7,970	$12,550	$18,460	$27,750	$34,860	e
Total	$38,710	$61,070	$96,230	$141,510	$212,750	$267,290	

Table 3-6

W/W Cost Model Capital Cost Breakdown by Percentage for Sedimentation Basins

Cost Component	Area ($A = ft^2$) and Length x Width (LW = ft x ft)						Average Percent
	A=240 LW = 30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation and Sitework	2.74%	3.27%	3.18%	3.31%	3.14%	3.03%	3.11%
Manufactured Equipment	22.06%	19.78%	25.43%	22.63%	27.96%	23.73%	23.10%
Concrete	7.67%	8.99%	8.76%	9.06%	8.55%	8.26%	8.55%
Steel	16.53%	21.47%	20.20%	23.05%	24.09%	26.07%	21.90%
Labor	16.07%	18.44%	18.00%	18.65%	17.66%	16.95%	17.63%
Pipes and Valves	17.98%	12.12%	9.46%	8.83%	7.57%	8.02%	10.66%
Electrical	3.90%	2.88%	1.93%	1.43%	0.99%	0.90%	2.01%
Contingencies	13.05%	13.05%	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

3.2.3 Implementing TDP Recommended Costing Upgrades

The capital cost breakdowns presented above and in the appendices of this document can be used to estimate the modified capital cost (i.e., the capital cost estimate developed using the TDP recommendations). The following sections briefly demonstrate how the capital cost breakdowns are applied, and how modified capital cost estimates are generated.

3.2.3.1 VSS Model

1. The VSS model presents capital and O&M costs as functions of design and average flow, respectively. Accordingly, the capital cost equation for package microfiltration units is:

   CAP = 0.86[DES] + 41.1

   Where: CAP = Total Capital Cost, $1,000s
   DES = Design Treated Flow, kgpd

2. Thus, for a 0.024 mgd (24 kgpd) plant the capital cost is:

   CAP = 0.86[24] + 41.1
   CAP = 61.74 or $61,740

3. The VSS model equations produce estimates in 1993 dollars. To escalate to September 1998, multiply the equation-generated capital cost by the ratio of the Engineering News Record (ENR) Building Cost Index for September 1998 to the 1993 index value.

   $61,740 x (3375/3009) = $69,250

   The escalated capital cost for a 0.024 mgd package microfiltration plant is $69,250.

4. Using the capital cost breakdown in Table 3-2, the total process cost is:

   $69,250 x 0.5697 = $39,452

5. The modified capital cost can then be calculated using the total cost factor presented in Table 3-1.

   $39,452 x 2.5 = $98,629

   Thus, the modified capital cost is $98,629.

3.2.3.2 Water Model

1. Assume the Water model output for a 0.27 mgd (270,000 gpd) package conventional treatment (coagulation/flocculation/filtration) plant is $692,066 (escalated to 1998 dollars).

2. Using the capital cost breakdown in Table 3-4, the total process cost is:

   $692,066 x (0.4136 + 0.0132 + 0.0752 + 0.0415 + 0.1630) = $488,945

3. The modified capital cost can then be calculated using the total cost factor presented in Table 3-1.

   $488,945 x 2.5 = $1,222,362

4. This approach must be applied to each unit process separately, then totaled for the entire treatment process to estimate the modified capital cost.

3.2.3.3 W/W Cost Model

1. Assume the W/W Cost model output for a 1 mgd (1250 sq ft.) rectangular sedimentation basin is $416,574 (escalated to 1998 dollars).

2. Using the capital cost breakdown in Table 3-6, the total process cost is:

   $416,574 x (0.2311 + 0.0855 + 0.2190 + 0.1066 + 0.0201) = $275,897

3. The modified capital cost can then be calculated using the total cost factor presented in Table 3-1.

   $275,897 x 3.33 = $918,737.

4. This approach must be applied to each unit process separately, then totaled for the entire treatment process to estimate the modified capital cost.

3.2.4 Cost Indices and Unit Costs

Both the Water Model and the W/W Cost Model require a number of standard indices and various unit costs from the Bureau of Labor Statistics, the Engineering News Record, and other referenced sources. The values used in conjunction with the development of cost estimates are reported in Tables 3-7 and 3-8.

Table 3-7

Costs Indices Used in the Water and W/W Cost Models

COST INDICES		
Description	**Index Reference**	**Numerical Value**
General Purpose: -Machinery -Concrete	 BLS 114[1] BLS 132[1]	 445.1[3] 448.8[3]
Steel	BLS 1017[1]	405.1[3]
Skilled Labor	ENR[2]	5317.36
Pipes & Valves	BLS 1149[1]	521.5[3]
Electrical	BLS 117[1]	281.8[3]
Buildings	ENR[2]	3375.31
PPI Finished Goods	BLS[1]	364[3]

[1] BLS - Bureau of Labor Statistics
[2] ENR - Engineering News Record
[3] BLS numerical values were re-based to 1967 base year (see Section 3.2.5)

Table 3-8

Costs Used in the Water and W/W Cost Models

CHEMICAL COSTS		OTHER COSTS	
Chemical	**Cost ($/ton)[1]**	**Description**	**Costs**
Alum	$300.00/ton	Electricity ($/KWH)	0.080[2]
Ferrous Sulfate	$350.00/ton	Land ($/Acre)	Various [3]
Hexametaphosphate	$1276.00/ton	Natural Gas ($/cu.ft.)	0.0060[2]
Lime, Quicklime	$116.00/ton	Diesel Fuel ($/gal)	0.66[2]
Sodium Chloride	$99.00/ton	Labor ($/hr)	30.00[4]
Sodium Hydroxide (50% Solution)	$371.00/ton	Large System Labor Rate[5]	$40.00/hour
Sulfuric Acid	$116.00/ton	Small System Labor Rate[5]	$28.00/hour

[1] Chemical costs are based on the values reported in the 1992 T&C document for Radionuclides escalated to 1998 dollars using the BLS, Chemical & Allied Products Index.
[2] Energy Information Administration Survey, U.S. Department of Energy
[3] Land costs are not included.
[4] ENR - Engineering News Record
[5] Technical Design Panel (EPA, 1998a)

This document presents total capital costs and annual O&M costs. Annual O&M costs include the costs for materials, chemicals, power and labor. Annualized costs can be determined using the following equations:

$$\text{Total annual cost (¢/kgal)} = \text{Annualized Capital Cost (¢/kgal)} + \text{O\&M Cost (¢/kgal)}$$

Where:

$$\text{Annualized Capital Cost} = \frac{\text{Capital Cost (\$)} * \text{Amortization Factor} * 100\text{ ¢/\$}}{\text{Average Daily Flow (mgd)} * 1000\text{ kgal/mgal} * 365\text{ days/year}}$$

$$\text{O\&M Cost (¢/kgal)} = \frac{\text{Annual O\&M (\$)} * 100\text{ (¢/\$)}}{\text{Average Daily Flow (mgd)} * 1000\text{ kgal/mgal} * 365\text{ days/year}}$$

Amortization, or capital recovery, factors for interest rates of 3, 7, and 10 percent for 20 years are reported in Table 3-9. Alternative capital recovery factors can be calculated using the formula presented below.

$$\text{Capital Recovery Factor} = i(1 + i)^N / (1 + i)^N - 1$$

Where: i = interest rate
N = number of years

Table 3-9

Amortization Factors

Interest Rate (%)	Amortization Period	Amortization Factor
3	20	0.0672157
7	20	0.0943929
10	20	0.1174596

3.2.5 Re-Basing Bureau of Labor Statistics Cost Indices

The Water Model and W/W Cost Model uses BLS cost index information based to 1967. In 1986, the BLS conducted a comprehensive overhaul of the industrial price methodology resulting in a re-basing of all index information to a 1982 = 100 base year. This requires a re-basing of BLS index information to 1967 prior to use in the models for the development of cost estimates. Table 3-10 provides the re-base factors. A sample re-base calculation is presented below.

Sample Rebase Calculation:

Machinery = 1982 Base Factor / Rebase Factor = 1967 Base Factor

= 147.8 / 0.32895016 = 449.3

Table 3-10

Bureau of Labor Statistics Rebase Information

BLS Series:	Index Reference	1982=100 Number	Re-base Factor (1)	1967=100 Number	Date
Machinery	BLS 114	147.8	0.32895016	449.3	9/98
Concrete	BLS 132	148.8	0.32261652	461.2	9/98
Steel	BLS 1017	113.3	0.28608856	396.0	9/98
Pipes & Valves	BLS 1149	162.2	0.30909034	524.8	9/98
Electrical	BLS 117	120.8	0.43185069	279.7	9/98
PPI Finish Goods Index	BLS 3000	130.6	0.35633299	366.5	9/98

(1) Provided by the BLS

3.2.6 Flows Used in the Development of Costs

Flow categories were developed to provide adequate characterization of costs across each of the flow regions presented in Section 3.2.1. A minimum of four data points were generated for each of the flow regions, with the exception of the transition regions, where cost estimates are based upon a linear regressions between the last data point of the previous region and the first data point of the following region. Table 3-11 presents the design and average flows, and cost models used in this process.

Table 3-11

Flows Used in the Cost Estimation Process

Design Flow (mgd)	Average Flow (mgd)	Cost Model
0.010	0.0031	VSS
0.024	0.0056	VSS
0.087	0.024	VSS
0.10	0.031	VSS
0.27	0.086	Water
0.45	0.14	Water
0.65	0.23	Water
0.83	0.30	Water
1.0	0.36	Water
1.8	0.7	W/W Cost
4.8	2.1	W/W Cost
10	4.5	W/W Cost
11	5	W/W Cost
18	8.8	W/W Cost
26	13	W/W Cost
51	27	W/W Cost
210	120	W/W Cost
430	270	W/W Cost

Shaded rows represent data used in the estimation of costs with the transition regions.

3.3 COSTS FOR MULTIPLE REMOVAL PERCENTAGES

Capital and O&M cost estimates are presented for the maximum achievable removal in this document. Table 3-13 presents a removal technology matrix which identifies maximum removal percentages for each radionuclide and technology combination. Costs for facilities requiring less than the maximum removal to meet individual radionuclide MCLs can be estimated using the blending approach discussed in Section 3.3.2.

3.3.1 Removal and Accessory Costs

Costs for each of the removal technologies discussed in this document can be separated into two categories: removal and accessory. Accessory costs include raw and finished water pumping, and clearwell storage. Removal costs include any process item directly associated with the removal of a particular contaminant, e.g., the ion exchange bed in ion exchange processes.

Accessory costs are independent of the desired removal percentage. For example, a one mgd treatment plant must still pump one million gallons of raw water into the plant, pump one million gallons of finished water, and have adequate storage (10% of daily production). Conversely, removal costs are dependent upon the desired removal. If contaminant levels are such that the plant need only remove 30 percent of the contaminant to reach the treatment goal, then the treatment process can be scaled to treat a portion of the flow. The treated flow is then blended with the untreated portion prior to distribution. Section 3.3.2 discusses the blending approach used in the development of cost estimates.

Cost estimates presented in the body of this document do not include accessory capital and O&M. Cost curves and equations for accessory costs (i.e., raw and finished water pumping, and clearwell storage) are presented in Appendix D.

3.3.2 Use of Blending in Cost Estimates

Capital and O&M costs were estimated using the VSS, Water, and W/W Cost models. If raw water contaminant levels are sufficiently low, a utility may not need to achieve maximum removal to achieve a treatment goal. For example, assume a facility is considering installation of a coagulation/filtration facility for uranium removal. The maximum achievable removal is expected to be 80 percent. If the raw water uranium concentration is 40 pCi/L and the treatment objective is a finished water concentration of 20 pCi/L, the utility need only remove 50% of the uranium in the raw water. In this scenario, the facility could treat a portion of the raw water and blend with untreated water and still achieve its treatment objective. The portion of the total process flow to be treated can be calculated using the following equation:

$$Q_{treated} = \frac{Q_{total}}{[((C_{max} - C_{desired})/C_{desired}) + 1]}$$

Where:
$Q_{treated}$ = Treated portion of the total process flow, mgd
Q_{total} = Total daily process flow, mgd
C_{max} = Maximum achievable removal efficiency, %
$C_{desired}$ = Desired removal efficiency, %

If 1 is substituted for the total daily flow (Q_{total}) in the above equation, the treated portion of the flow ($Q_{treated}$) is expressed as a fraction of the total flow. Multiplying that fraction by the total plant flow will result in design and average operating flows that can be used to estimate capital and O&M costs for the treated portion of the flow, using the cost curves and equations presented in this document.

3.4 ADDITIONAL CAPITAL COSTS

The cost models discussed in the previous sections are good tools for estimating capital and O&M costs associated with various drinking water treatment technologies. There are additional capital costs, however, which the models do not account for and which may be a very real expense for public water utilities. The need for additional capital costs can be affected by a number of factors, including: contaminants present, quality of the source water, land availability, retrofit of existing plants, permitting requirements, piloting issues, waste disposal issues, building or housing needs, and redundancy. Tables with additional capital cost estimates for each technology discussed in this document are presented in Appendix E.

Contaminants

The radionuclides with which this document is concerned are uranium, radium, polonium-210, lead-210, and alpha and beta emitters. A number of technologies have been proven to be effective in removing radionuclide contamination from source waters, and are discussed in detail in this document as well as in the 1992 T&C document (EPA, 1992). The presence of other contaminants (e.g., metals, pathogens, organics) can raise additional treatment concerns and result in decreased process performance.

Water Source

Uranium, radium, lead, polonium, and other alpha emitters are more common in ground waters, while beta emitters are found in surface waters. Surface waters generally contain higher levels of suspended and dissolved solids which can affect removal efficiency. Facilities combining plant influent from multiple sources also can affect source water quality.

Land

Land requirements were calculated based upon TDP recommendations (EPA, 1997) and engineering judgement. Appendix E presents two scenarios for land costs. The low cost scenario assumes land costs to be $1,000 per acre for small systems (i.e., less than 1 mgd) and $10,000 per acre for large systems. All land costs are $100,000 per acre for the high cost scenario (EPA, 1998b).

Retrofitting

All costs presented in this document are for new construction, with the exception of the enhanced coagulation and enhanced lime softening processes. All processes contained in the cost models include pipes and valves, electrical and instrumentation, and other costs associated with retrofitting. It was assumed that the costs included are sufficient for the retrofit of existing coagulation/filtration and softening plants. As a result, costs for retrofitting are excluded from Appendix E.

Permitting

Permitting costs follow the recommendations of the TDP as presented in the *Technology Design Conference Information Package* (EPA, 1997). A technology-specific summary of low and high cost permitting scenarios is presented in Table 3-12. The number of permits required can vary by location, depending upon State and local regulations, as well as technology. Some technologies may require permitting for storage tanks used for process chemicals, while others may necessitate NPDES permits if the disposal option for process residuals is to discharge to a nearby surface water.

Piloting

Piloting costs are neglected in this document and are not included in Appendix E.

Waste Disposal

Costs associated with the disposal of radionuclide-containing waste streams are presented in Chapter 12 of this document. Residuals handling and disposal methods for waste from each treatment process are discussed and cost estimates are presented in tabular format. EPA has published two manuals, *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993a) and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b), which present cost equations for each disposal option discussed in this document, as well as others not discussed. These documents are the basis for the cost estimates provided here.

Storage/Building

All of the cost models used in preparing this document include costs for housing of equipment. It is assumed that the costs included in the model output are sufficient. As a result, additional building costs are not included in Appendix E. It is also assumed that source water production is consistent and storage for raw waters is not necessary.

Table 3-12
Permitting Scenarios

Permit Type	CF[2]	MCF[2]	LS[2]	MLS[2]	AE[2]	CE[2]	RO[2]	EDR[2]	GF[2]	DF[2]	I-LF[2]	AA[2]
Possible Permits for All Technologies[3]												
Land Development	H	H	H	H	H	H	H	H	H	H	H	H
Stormwater Management	H	H	H	H	H	H	H	H	H	H	H	H
Soil Erosion & Sediment Control	H	H	H	H	H	H	H	H	H	H	H	H
Building	H	H	H	H	H	H	H	H	H	H	H	H
Potable Water	B	B	B	B	B	B	B	B	B	B	B	B
Technology Specific Permits[3]												
Sludge Disposal	B	B	B	B			B	B	B	B	B	
Air Quality												
NPDES	B	B		B	B	B	B	B	B	B	B	
UIC												
Site Dependent Permits[3]												
OSHA												
UST/AST Registration												
Stormwater NPDES	H	H	H	H	H	H	H	H	H	H	H	H
SPCC Plan	B	B	B	B	B	B	B	B	B	B	B	
Highway Occupancy	H	H	H	H	H	H	H	H	H	H	H	H
Rodent & Insect Control	H	H	H	H	H	H	H	H	H	H	H	H
EA/EIS	H	H	H	H	H	H	H	H	H	H	H	H
Building Occupancy	H	H	H	H	H	H	H	H	H	H	H	H
Wetlands	H	H	H	H	H	H	H	H	H	H	H	H

1 Based upon *Technical Design Conference Information Package* (EPA, 1997)
2 CF - Coagulation/Filtration, MCF - Modified Coagulation/Filtration, LS- Lime Softening, MLS - Modified Lime Softening, AE - Anion Exchange, CE - Cation Exchange, RO - Reverse Osmosis, EDR - Electrodialysis Reversal, GF- Greensand Filtration, DF- Direct Filtration, I-LF- In-Line Filtration, AA - Activated Alumina
3 L - Low Cost Scenario, H - High Cost Scenario, B - Both Low and High Cost Scenario

Redundancy

The cost models include standby pumps for some of the unit processes used in generating the cost estimates presented in this document (e.g., raw and finished water pumping). Further, it is good design practice to include additional filtration structures and sedimentation basins to allow continued operation during maintenance of one or more of the structures. Backup pumps are not included for chemical feed systems. As a result, there may be some additional capital costs associated with redundancy for these items. *Recommended Standards for Water Works* (Great Lakes Upper Mississippi River Board of State Public Health and Environmental Managers, 1997), often referred to as the Ten State Standards, presents a comprehensive discussion of redundancy and recommended redundant items. The Ten State Standards was used for presenting costs for redundant items in Appendix E.

3.5 APPLICABILITY OF TECHNOLOGIES

This document presents capital and O&M cost estimates for six radionuclide removal technologies (enhanced coagulation, lime softening, anion and cation exchange, reverse osmosis, and greensand filtration) for drinking water. It also discusses the relative effectiveness of six additional technologies (coagulation/filtration, direct and in-line filtration, enhanced lime softening, electrodialysis reversal and activated alumina). The effectiveness of each technology was evaluated with respect to each of the contaminants discussed in Chapter 2. Table 3-13 summarizes the technologies presented, the contaminants for which the technology has demonstrated effectiveness, and the removal percentages for which costs are presented in this document.

Table 3-13
Technology and Contaminant Maximum Removal Efficiency Matrix

Technology	Radium	Uranium	Polonium-210	Lead-210	Alpha Emitters	Beta Emitters
Coagulation/Filtration	NA	80	NA	95	NA	80
Enhanced Coagulation[1]	NA	30	NA	45	NA	30
In-Line Filtration	NA	70	NA	NA	NA	NA
Lime Softening	85	85	NA	95	NA	90
Enhanced Lime Softening[1]	35	35	NA	45	NA	40
Anion Exchange	NA	95	70	NA	NA	NA
Cation Exchange	80	NA	NA	NA	80	90
Reverse Osmosis	80	95	90	95	90	90
Electrodialysis Reversal	80	95	NA	95	NA	NA
Greensand Filtration	70	NA	NA	NA	NA	NA
Direct Filtration	NA	70	NA	NA	NA	NA
Activated Alumina	NA	95	NA	NA	NA	NA

NA = Not applicable, or no data was found to support the effectiveness of this technology for removing the specified contaminant.

1- Removal efficiencies for enhanced coagulation and enhanced lime softening are based upon additional removals. These processes typically remove 50 percent of the specified contaminant prior to enhancement. Thus, the 30 percent removal estimates are for a total 80 percent removal (50 from existing operation, 30 resulting from the enhancement).

4.0 COAGULATION/FILTRATION AND ENHANCED COAGULATION

4.1 PROCESS DESCRIPTION

Coagulation/Filtration (C/F) is a treatment process that alters the physical or chemical properties of colloidal or suspended solids, enhancing agglomeration, and enabling these solids to settle out of solution by gravity or to be removed by filtration. Coagulants change the surface charge of solids to enable agglomeration or enmesh particles into a flocculated precipitant. The final products are larger particles, or floc, that settle more readily under the influence of gravity, or are more easily removed by filters. Coagulants commonly used include aluminum sulfate (alum), ferric and ferrous sulfate, ferric chloride, and polyelectrolytes.

Processes included in a conventional C/F plant are rapid mix, flocculation, sedimentation, filtration, surface wash, and clearwell storage. Removal efficiency is dependent on the type and dosage of preoxidant (if used), the type and dosage of coagulant, the pH, and the influent contaminant characteristics and concentration. Enhanced coagulation involves modifications to the typical C/F process such as increasing the coagulant dosage, reducing the pH, or both. The process is nearly identical to that of conventional C/F with those two exceptions.

Direct filtration (DF) operates under the same principles as coagulation/filtration, and includes all the components of C/F except sedimentation/clarification prior to filtration. DF may be more suited for waters containing lower levels of contaminants (e.g., solids, color) because lower amounts of floc are produced which can be removed by filtration without a sedimentation/clarification stage. For DF to be effective for removal of radionuclides, the raw water turbidity should not exceed 10 NTU. According to the *Small System Compliance Technology List for the Surface Water Treatment Rule* (EPA, 1997), the National Research Council (NRC) has suggested that small systems not use DF for waters with average turbidities above 10 nephelometric turbidity units (NTU) or maximum turbidities above 20 NTU. Also, the performance of DF is extremely sensitive to the ability of a skilled operator to properly manage the coagulation chemistry, and EPA suggests that only systems with access to a full-time operator utilize DF.

In-line filtration (ILF) is the simplest form of DF, consisting of filters preceded by chemical feed and mixing. Chemicals are introduced into the filter influent pipeline and mixed with a static mixer. Influent pipeline turbulence satisfies flocculation requirements. The major components of a basic ILF system include: chemical feed systems, static (in-line) mixing, filtration, surface wash facility, backwash, and clearwell storage. Like DF, ILF normally requires less coagulant than C/F. For effective utilization of in-line filtration, raw water must be of seasonally uniform quality with turbidity less than 10 NTU.

4.2 APPLICABILITY

Radionuclides occurring as suspended particles in water may be removed effectively by coagulation and filtration processes. However, the removal of soluble radionuclides is governed by the reaction between the radionuclides and the chemicals added in treatment. Laboratory studies suggest that coagulation is more effective for removal of soluble cations of valence 3, 4, or 5 than for lower valence cations (EPA, 1986).

4.2.1 Radium

Chemically, radium exists principally as a cation of valence 2, making it similar to calcium in its chemical affinities. For this reason, C/F treatment is not expected to be effective for the removal of radium-226 and -228. On the other hand, lime softening, ion exchange, reverse osmosis, and electrodialysis reversal have been effective for radium. These treatment technologies are discussed in Chapters 5, 6, 7, and 8, respectively.

4.2.2 Uranium

The 1992 T&C document (EPA, 1992) reviewed numerous studies indicating that C/F is capable of removing between 80 and 95 percent of influent uranium levels, the effectiveness being highly dependent on the raw water pH and the coagulant type and dosage. High removals of uranium (95 percent) were achieved with alum dosages greater than 10 mg/L at a pH of 10. Iron coagulant also resulted in higher uranium removals at pH 10, with removals of 80 percent and 93 percent for ferric and ferrous sulfate, respectively (EPA, 1986).

If uranium removal is required for a water that is already treated using C/F, modification of the existing process to accommodate coagulant dosage and pH adjustment (i. e. enhanced coagulation) may be a cost-effective alternative. However, because higher removals are apparently achieved only at high pH levels, when greater than 95 percent uranium removal is required C/F may not be a good choice. C/F is more appropriate when less than 80 percent removal is required.

Engineered C/F treatment (i.e. in which individual unit processes must be designed) is generally not suitable for smaller water systems due to the relatively high costs and technical complexity of operation and maintenance (EPA, 1997). Package conventional treatment plants are available which makes this technology viable for small systems. A high-rate sedimentation or solids removal process and the use of filtration rates of 12 to 17 m/h (5 to 7 gpm/sf) is key to an affordable C/F system for small systems (NRC, 1996).

4.2.3 Polonium

Due to the lack of data and case studies for the removal of polonium-210 (Po-210) by C/F, polonium-210 was not included in the capital and O&M cost estimates.

4.2.4 Lead

Studies have indicated that the removal of lead (Pb) by C/F can be as high as 99 percent throughout a pH range of 6 to 8, depending on the raw water source (Sorg and Logsdon, 1978). Both alum and iron coagulants are very effective in removing lead from raw water sources with high turbidity; however, alum coagulant is less effective in the removal of lead from ground water (low turbidity). Alum doses of 10, 20, 30, 50, and 100 mg/L with ground water achieved 52, 72, 79, 86, and 92 percent removals, respectively (Sorg and Logsdon, 1978). Ferric sulfate is more effective than alum in removing lead from raw waters when initial lead concentrations are high. Due to the high percentage removals of lead in conventional C/F plants, it is assumed that modifications to an existing C/F plant should result in similar removals (Sorg and Logsdon, 1978).

4.2.5 Gross Alpha Particle Activity

In addition to the alpha-emitting radionuclides discussed above, gross alpha particle activity may be caused by the radionuclides plutonium-239 (Pu-239) and thorium-232 (Th-232), among others. Because of their tendency to be high-valence cations, Pu-239 and Th-232 may be amenable to removal by C/F methods. However, definitive studies of their removal by C/F are scarce. The removal of plutonium was studied at three water treatment facilities that use Savannah River water, one upstream and two downstream from the Savannah River Nuclear Power Plant (Corey and Boni, 1975). The treatment facility upstream of the power plant used sand and anthracite filters, and achieved a plutonium removal efficiency of 79 percent. Both downstream treatment facilities used a combination of coagulation, sedimentation, and filtration to reduce their initial plutonium concentrations of 0.99 fCi/L and 2.25 fCi/L by 92 percent and 96 percent, respectively. In these three cases, the treatment efficiency increased with higher plutonium concentrations in the raw water.

4.2.6 Beta Particle Activity

Beta particle activity may be caused by the radionuclides strontium-90 (Sr-90), tritium, and iodine-131 (I-131) among others. More than 90 percent removal of strontium is accomplished by iron coagulant dosages greater than 500 mg/L and at a pH of 11 (EPA, 1986). With alum used as a coagulant and silica for enhancing coagulation, the removal efficiencies of I-131 ranged from 28 to 87% (EPA, 1986). Iron, copper sulfate, and silver nitrate were also effective as coagulants for the removal of I-131.

4.3 DESIGN CRITERIA

The major design criteria and assumptions used to estimate costs for enhanced coagulation treatment systems are summarized below. These criteria were based upon the April 1999 Radionuclides T&C document, the November 1999 Arsenic T&C documents and the cost models used to estimate treatment costs: (1) the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993) for small systems; (2) the Water Model (Culp/Wesner/Culp, 1984) for intermediate systems; and (3) the W/W Cost Model (Culp/Wesner/Culp, 1994) for large systems. The VSS and Water Models assume package treatment plants are available. Details of the design criteria can be found in these documents.

- Coagulation Feed System: Ferric chloride is dosed at 35 mg/L.
- Polymer feed system: Polymer is dosed at 0.4 mg/l for small systems. 2mg/l for intermediate and large systems.
- Rapid Mix: Detention time is 1 minute at design flow.
- Flocculation: Design detention time is 20 minutes.
- Sedimentation: Rectangular sedimentation basins with an overflow rate of 1,000 gpd/ft^2.
- Gravity Filtration System: Filters operate at a loading rate of 2.5 gpm/ft^2 for small systems, 5.0 gpm/ft^2 for intermediate and large systems.
- Filtration Media: Dual media filters are used.
- pH Adjustment: Lime is dosed at 35 mg/L.

4.4 TREATMENT COST

From a general perspective, coagulation/filtration as a newly installed technology is less effective than other technologies, and can be cost prohibitive, particularly for small and very small systems. However, if a facility already utilizes coagulation/filtration, process enhancement (i.e. enhanced coagulation) is very effective and more cost efficient than installation of additional treatment processes, such as ion exchange. Consequently, capital and O&M costs estimates in this document were generated for enhanced coagulation only.

For the purpose of estimating costs of enhanced coagulation, it was assumed that a typical C/F treatment plant could remove 50 percent of the influent radionuclide prior to modification, i.e., enhancement. It was also assumed that the only added O&M burden would result from power and materials costs, and no additional labor was assumed to be required. Costs presented are for the enhancement only, and are in addition to any current annual debt incurred by the utility.

The treatment costs presented in this section are based on the design criteria provided in section 4.3 above, using the cost models described in Section 3.2. Figures 4-1 and 4-2 represent the capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide groups in question, as shown in Table 4-1.

Table 4-1

Enhanced coagulation/filtration

Radionuclides maximum removal percentages

Radionuclide group	**Maximum removal percentage (%)**
Radium	NA
Uranium	80
Polonium	NA
Lead	95
Alpha emitters	NA
Beta emitters	80

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

Curve fitting analysis was conducted on the modeled cost estimates, and include the use of transition flow regions to improve the estimates within the breakpoints between models.

Figure 4-1
Enhanced Coagulation/Filtration
Capital Costs

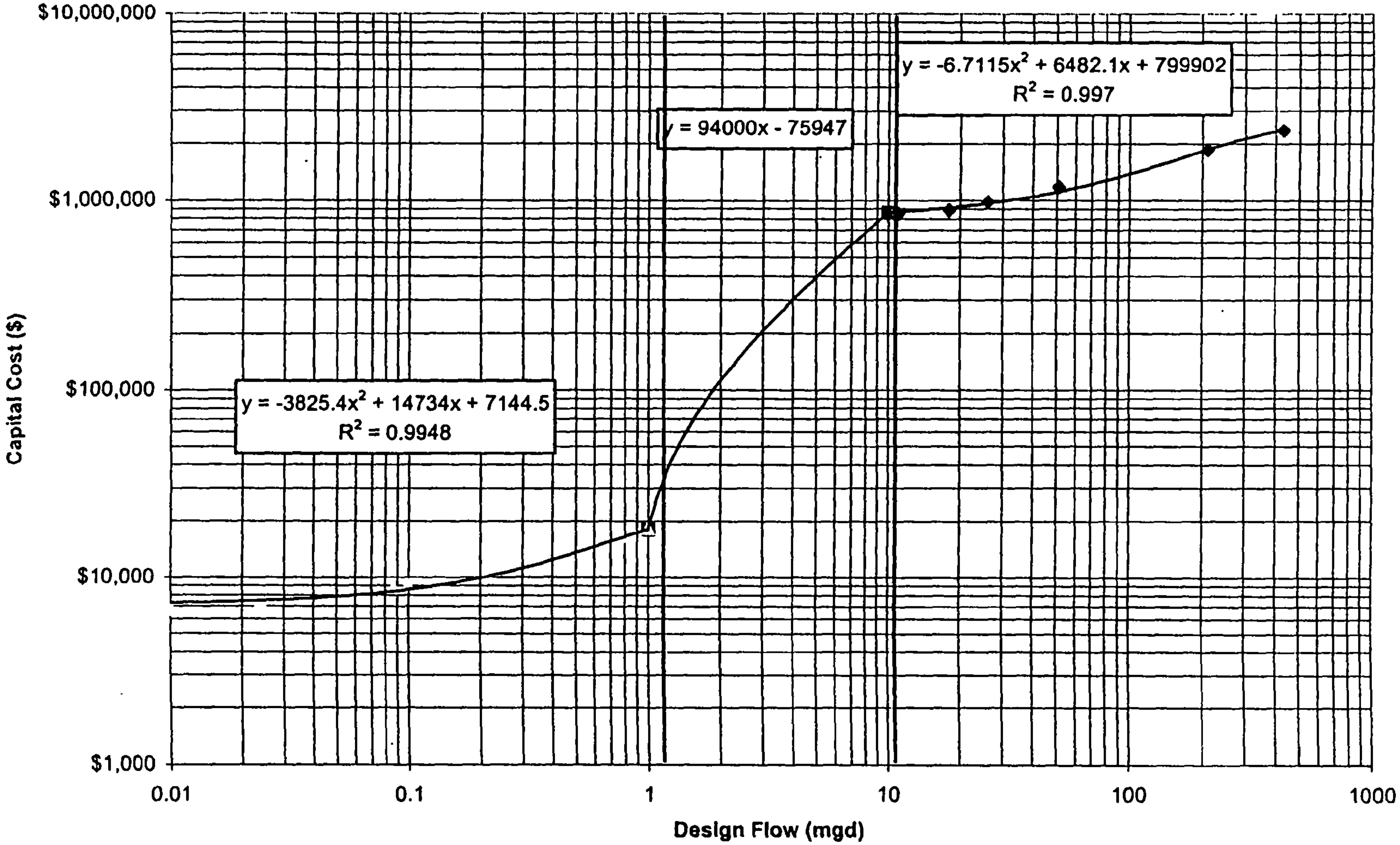
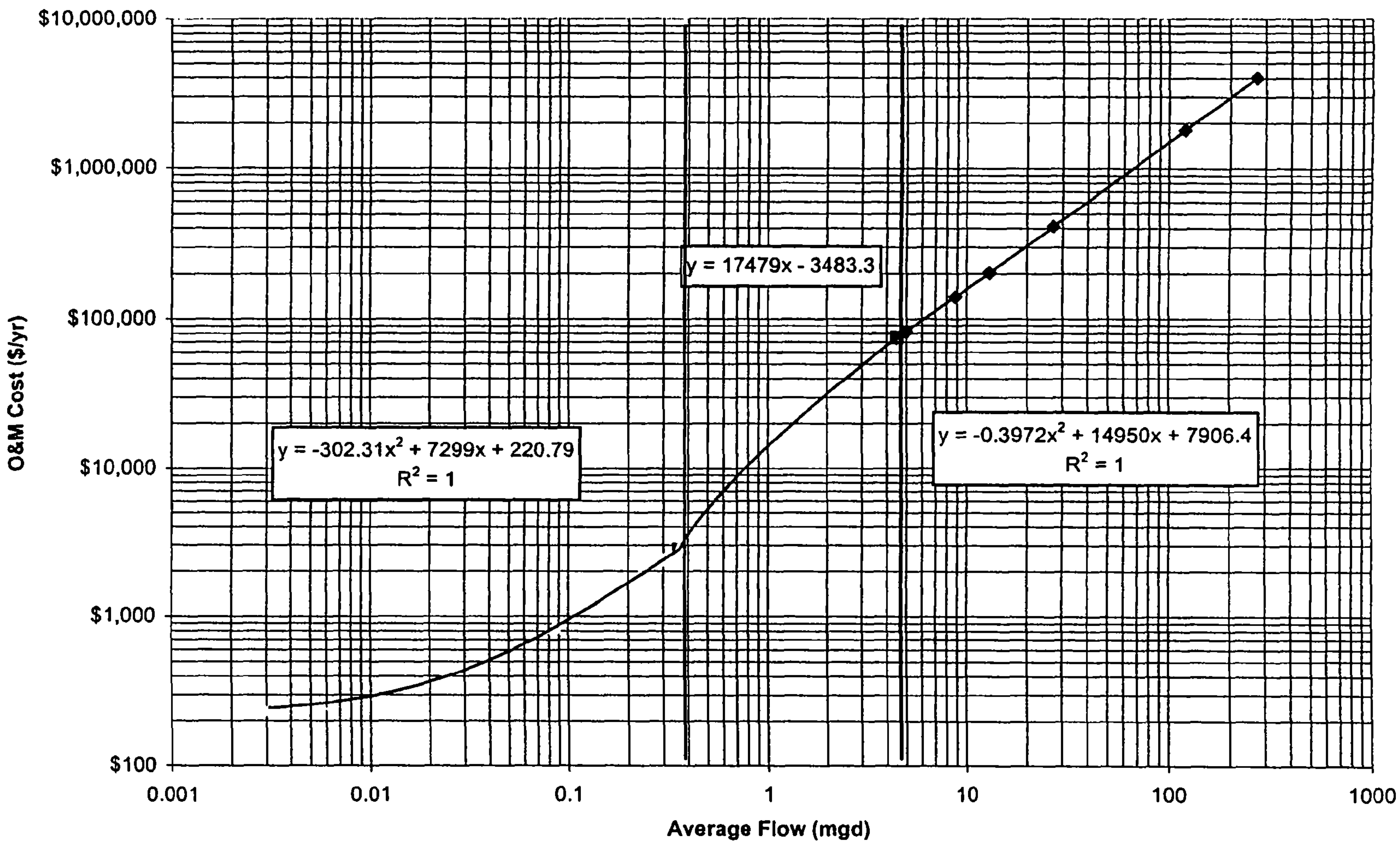


Figure 4-2
Enhanced Coagulation/Filtration
O&M Costs



5.0 LIME SOFTENING

5.1 PROCESS DESCRIPTION

In most waters, hardness is caused by the presence of calcium and magnesium ions. The addition of lime or lime and soda ash will partially remove these ions, thereby softening the water. The use of lime and soda ash for softening is dependent upon several raw water quality parameters, including calcium hardness, magnesium hardness, carbonate alkalinity, and pH. The addition of lime to water increases pH and causes a shift in carbonate equilibrium, which in turn causes calcium to precipitate as calcium carbonate. Soda ash (sodium bicarbonate) is added if insufficient alkalinity is present in the water to precipitate calcium to the desired levels. For magnesium removal, excess lime is added to increase pH, which results in the precipitation of magnesium hydroxide.

A typical lime softening (LS) plant includes chemical addition, upflow contactor, recarbonation (if necessary), and filtration. Modifications to an existing LS system by increasing lime dose and pH (i.e. enhanced softening) may improve the removal of specific contaminants, including radionuclides, present in the source water. Lime softening is not widely used by small systems because the process requires full-time personnel and is generally more expensive than automated ion exchange softening systems. However, small package plants with labor-saving features are becoming more feasible, making LS more applicable for small community systems.

5.2 APPLICABILITY

Construction of a lime softening plant is not considered a cost effective solution for the removal of radionuclides. However, lime softening can be a cost effective alternative when required for the reduction of hardness of source waters (EPA, 1986).

5.2.1 Radium

Radium removal by LS treatment is significantly affected by pH. Brink et al. (1978) evaluated the results of Ra-226 removal conducted at an EPA lime softening pilot plant in Cincinnati, Ohio. Lime softening at pH 9.5 resulted in radium removals of 79 percent for settled water and 84 percent for filtered water. Enhanced lime softening to pH 10.6 achieved 92 to 93 percent radium removal in the settled water, and 93 to 96 percent removal in the filtered water. Increased radium removals at higher pH levels were also noted in full-scale LS treatment plants (Brink et al., 1978).

5.2.2 Uranium

Treatability studies have shown that LS is capable of removing 85 to 90 percent uranium in the pH range of 10.6 to 11.5. Lee and Bondietti (1983) performed jar tests on pond water with a U-238 concentration of 56 pCi/L (0.083 mg/L) as uranyl tricarbonate; total alkalinity was 100 mg/L and magnesium concentration was 13 mg/L. The effects of various lime dosages alone, and lime dosages combined with magnesium carbonate, were evaluated at a variety of pH levels. 85 to 90 percent removal of uranium was achieved with lime dosages between 50 and 250 μg/L and an increase in pH from 10.6 to 11.5. The addition of magnesium carbonate, however, produced removals of over 95 percent at pH levels of 10.6 to 11.2 (Lee and Bondietti, 1983).

5.2.3 Polonium

Due to the lack of data and case studies for the removal of polonium-210 (Po-210) by LS, capital and O&M cost estimates were not generated.

5.2.4 Lead

At a pH level of 7 to 8.5, greater than 95 percent lead removal can be achieved by using lime softening (AWWA, 1990). Additional studies have indicated that the removal of lead by LS can reach as high as 99 percent throughout the pH range of 8.8 to 11 (Sorg and Logsdon, 1978). An increase in the amount of calcium carbonate hardness in the raw water source will increase the percentage of lead removal.

5.2.5 Gross Alpha Particle Activity

Very little research has been done on the removal by LS of the additional alpha emitters included in this document, Pu-239 and Th-232. Plutonium is a member of the actinide series of rare-earth elements. In water, plutonium forms low-solubility fluorides, hydroxides, and oxides, and forms relatively soluble complexes with citrate. Thorium forms relatively insoluble hydroxides and oxides, and readily soluble nitrates, sulfates, chlorides, and perchlorate salts. Because of their typically low valences, Pu-239 and Th-232 may be amenable to C/F removal, as discussed in Section 4.2.5. Other removal technologies, including cation exchange (Chapter 6) and reverse osmosis (Chapter 7), may also be appropriate for the removal of these radionuclides from drinking water.

5.2.6 Beta Particle Activity

Various studies have indicated that LS is a very effective measure for the removal of Sr from water. A combined dosage of lime and soda is needed to achieve Sr removals of 90 percent or better. The dose of 5 grams of lime and 5 grams of soda per gallon of raw water (gpg) has been shown to achieve 75 percent removal of Sr. A 7:9 grams lime:soda dose per gallon of raw water achieved 90 percent Sr removal, and a 20:20 grams lime:soda dose per gallon of raw water achieved 95 percent Sr removal (Lassovszky and Hathaway, 1983). Lime and soda-ash appear to be ineffective in the removal of I-131 (EPA, 1986).

5.3 DESIGN CRITERIA

The major design criteria and assumptions used to estimate costs for LS treatment systems are summarized below. These criteria were based upon the April 1999 Radionuclides T&C document, the November 1999 Arsenic T&C document, and the cost models used to estimate treatment costs: (1) the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993) for small systems; (2) the *Water Model* (Culp/Wesner/Culp, 1984) for intermediate systems; and (3) the *W/W Cost Model* (Culp/Wesner/Culp, 1994) for large systems. The VSS and Water Models assume package treatment plants are available. Details of the design criteria can be found in these documents.

- Lime Feed: Lime is dosed at 250 mg/L.

- Carbon Dioxide Feed: Carbon dioxide is dosed at 35 mg/L.
- Gravity Filtration System: Filtering loading rate = 5 gpm/ft^2.
- Filtration Media: Dual media.

5.4 TREATMENT COST

The treatment costs presented in this section are based on the design criteria provided in Section 5.3 above, using the cost models described in Section 3.2. Figures 5-1 and 5-2 represent the capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide groups in question, as shown in Table 5-1.

Table 5-1

Lime softening

Radionuclides maximum removal percentages

Radionuclide group	Maximum removal percentage (%)
Radium	85
Uranium	95
Polonium	NA
Lead	95
Alpha emitters	NA
Beta emitters	90

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

Curve fitting analysis was conducted on the modeled cost estimates, and include the use of transition flow regions to improve the estimates within the breakpoints between models.

Figure 5-1
Lime Softening
Capital Costs

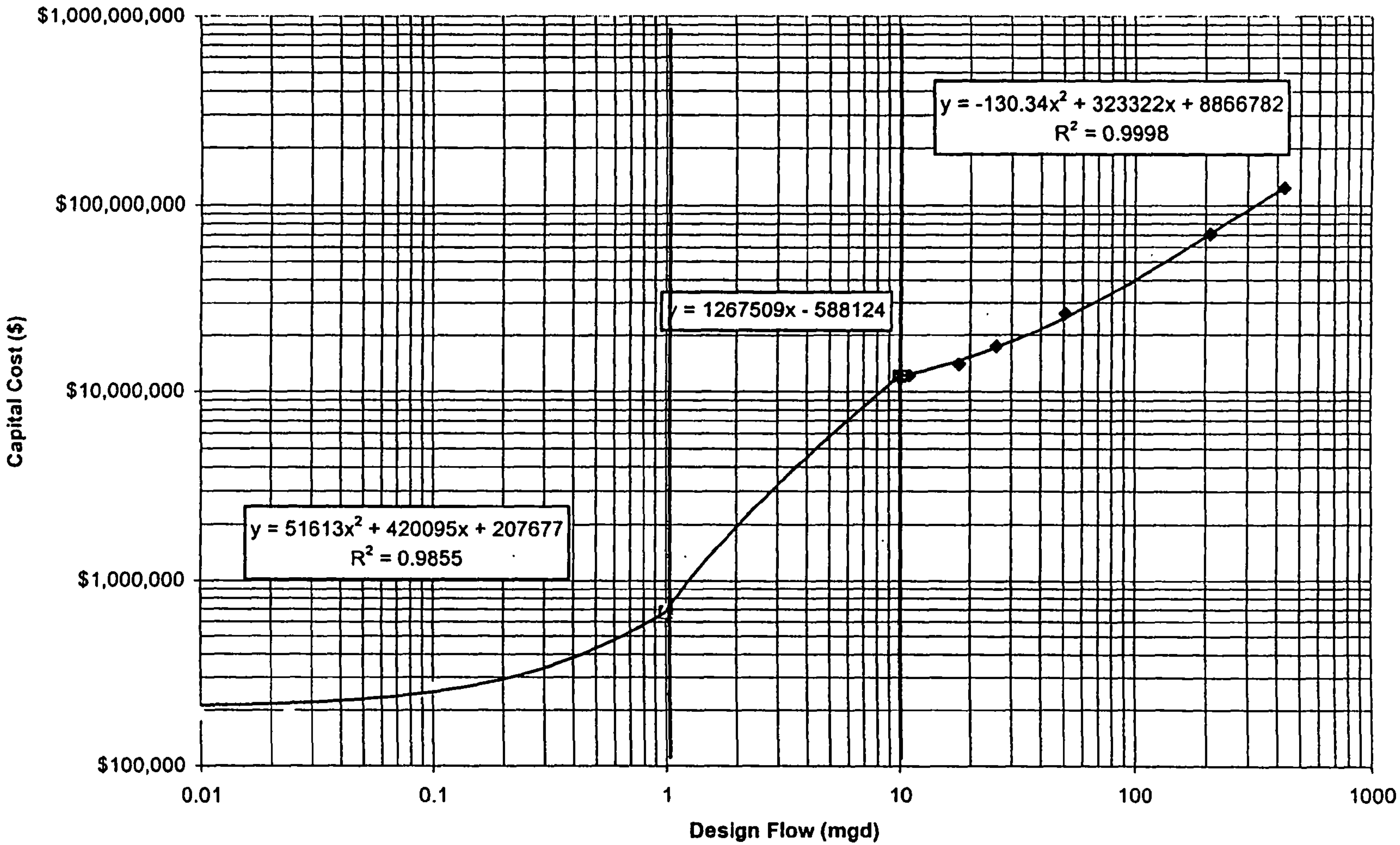
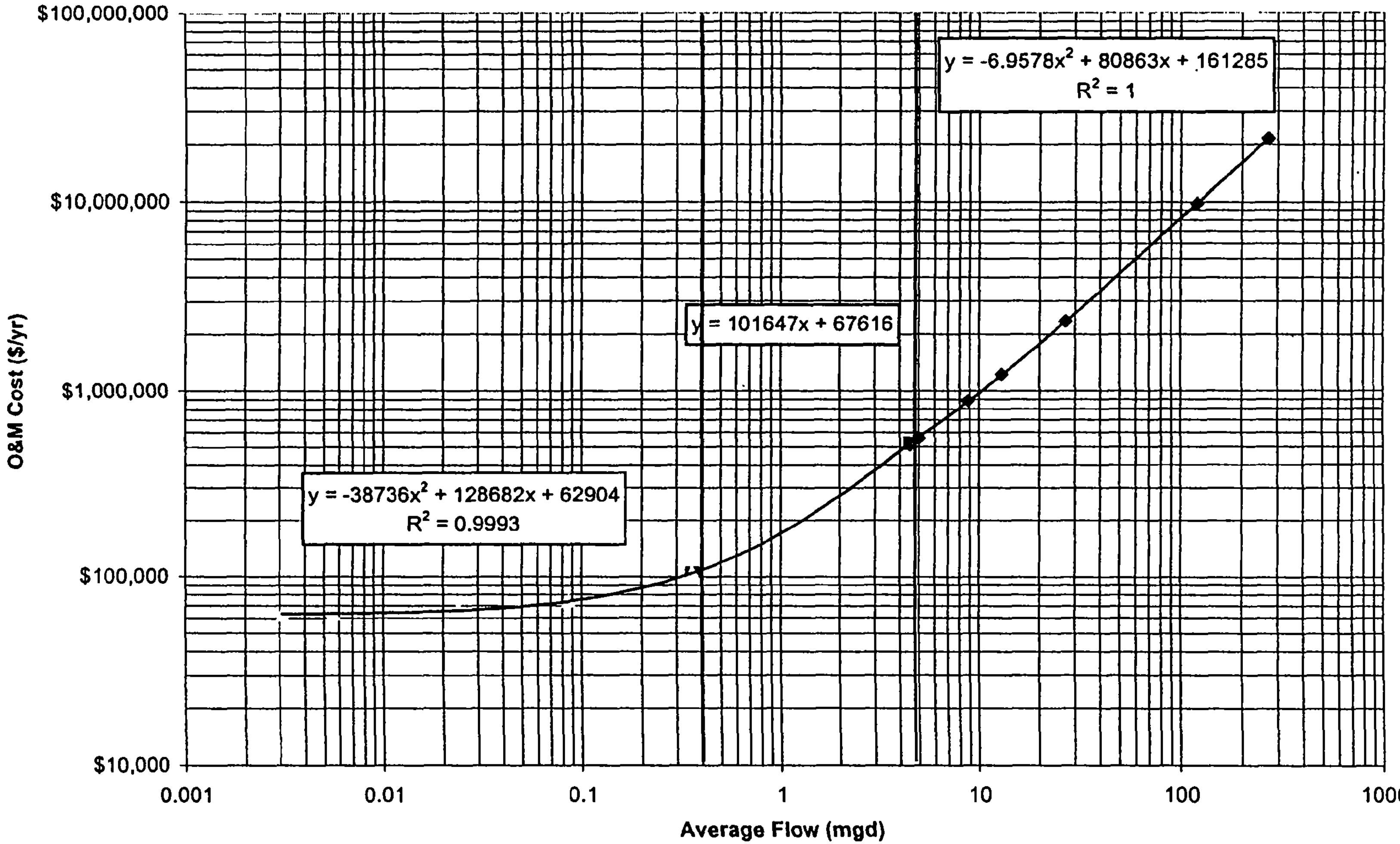


Figure 5-2
Lime Softening
O&M Costs



6.0 ION EXCHANGE

6.1 PROCESS DESCRIPTION

Ion exchange (IX) uses synthetic resins or natural zeolites to replace ions in the feed water with ions of similar charge initially fixed to the resin/zeolite matrix. Exchange resins are generally insoluble solids with fixed cations or anions capable of exchanging with similarly-charged mobile ions in the feed water. Cation exchange (CX) removes positively charged ions from the feed water, and anion exchange (AX) removes negatively charged ions. Ion selectivity, resin capacity, regeneration requirements, and mode of operation are important design parameters.

Ion selectivity refers to the preference for resins to exchange with specific ions. The most significant factor influencing ion selectivity is the magnitude of charge, or valence state, of the ion: an exchange resin has a greater preference for higher valence ions. For example, if cation $A^{(2+)}$ and cation $B^{(4+)}$ are both present in a raw water source, cation B is preferred over cation A. A second factor influencing ion selectivity is the hydrated radius of the ion: the resin has greater preference for ions of smaller hydrated radius. Because of the ion selectivity of IX resins, an IX system must be selected specifically to remove the contaminants of concern.

Resin capacity is the total quantity of ions that can be exchanged per unit of mass or volume of resin when the resin bed has been completely exhausted or has reached a selected breakthrough level. Resin capacity is a function of the type of resin, the composition and concentrations of the feed solutes, ion selectivity, the flow rate through the bed, the amount of regenerant used, temperature, and the desired quality of the product water. The resin capacity for a contaminant of concern is important because of its effect on process efficiency and system cost. A high exchange capacity resin permits the use of smaller resin beds and requires less frequent regeneration.

When the resin capacity is exhausted, the exchanger is removed from service and the resin is regenerated with a concentrated solution. Regeneration displaces ions exchanged during the IX process and returns the resin to near its original exchange capacity. Regeneration requirements are driven by four factors: regenerant volume, flow rate, concentration, and regeneration frequency. A typical regeneration operation includes: (1) an upflow backwash cycle to fluidize the resin bed and remove suspended solids; (2) a downflow regeneration cycle to replace the ions removed from the feed water with ions of the type originally attached to the resin; and (3) a downflow rinse cycle to remove excess regenerant from the resin bed.

There are two common modes of regeneration operation in IX systems: fixed-bed and continuous. In the continuous regeneration system, a portion of the resin is continuously regenerated, and a portion is continuously producing finished water. In a fixed-bed system, the IX process is interrupted while the resin bed is regenerated. Fixed bed ion exchangers are more commonly used for water treatment than continuous regeneration systems because they are simpler in both design and operation.

If the IX bed is operated beyond its exhaustion point for a specific contaminant, more strongly adsorbed compounds can displace the contaminant from the resin, and the bed effluent will contain a higher concentration of the contaminant than the raw water.

6.2 APPLICABILITY

Ion exchange processes can be effective tools for the removal of radionuclides from drinking water. However, because of the ion selectivity of exchange resins, the radionuclide(s) contributing to the radioactive emissions must be identified prior to treatment.

6.2.1 Radium

Cation exchange has been shown to be effective in the removal of radium in pilot and full-scale studies. In pilot studies, Lauch (1987) reported 99 percent removal of radium in a CX process using a strong acid cation resin. The influent water had a hardness of 200 mg/L as $CaCO_3$ and a radium concentration of 20 pCi/L. Radium effluent concentrations were less than 5 pCi/L when hardness breakthrough occurred. Brink et al. (1978) surveyed several cities that use sodium CX (zeolite) to remove radium from drinking water. His survey indicated that radium removals between 93 and 97 percent were achieved in five of the six systems investigated; the sixth system had a removal of 81 percent. Influent concentrations of radium ranged from 5.1 pCi/L to 43 pCi/L in these systems.

(Tamburini and Habenicht, 1992).

6.2.3 Polonium

Studies performed by Lowry in 1990 indicate that 70 percent removal of polonium (Po) by anion exchange is anticipated. The 70 percent removal assumes that regeneration should occur every 3700 bed volumes. According to the same study, removal of Po by means of a cation resin performed poorly.

6.2.4 Lead

There are limited data and case studies available for the removal of lead-210 (Pb-210) by IX, capital and O&M cost estimates were not generated. However, studies have indicated that lead is a highly preferred cation by strong-acid cation ion exchange resin, and ion exchange should be an effective method for lead removal (Sorg and Logsdon, 1978). Resins with chelating functional groups such as phosphoric acid or ethylenediaminetetracetic acid (EDTA) have been manufactured that have extremely high affinities for metals such as lead (Pb^{2+}) (AWWA, 1990). Additional research is needed to determine the efficiency of lead removal by ion exchange, and if the percent removal is pH dependent.

6.2.5 Gross Alpha Particle Activity

Few studies have been conducted to specifically assess the effectiveness of IX for the removal of the additional alpha-emitting radionuclides (Pu-239 and Th-232) addressed in this document. However, implications from related studies suggest that these alpha emitters may be effectively removed by CX technologies (EPA, 1992).

6.2.6 Beta Particle Activity

In a standard ion exchange softening reaction, sodium ions are exchanged for the hardness ion strontium (Sr^{2+}), thus allowing for Sr removal by cation exchange. Sources from the Oak Ridge National Laboratory indicate a 99.1-99.8 percent removal of Sr using a cation exchange resin, a 5-7 percent Sr removal by using an anion exchange resin, and a 99.95-99.97 percent Sr removal by using mixed-bed resins (Lassovszky and Hathaway, 1983).

6.2.2 Uranium

The effectiveness of IX for uranium removal has been assessed in numerous studies, which included small full-scale plants. A bench-scale study was conducted by Hathaway (1983) for the evaluation of uranium removal by AX resins. The resins evaluated included Donex 21K and Ionac A641 in source water with a pH between 7.4 and 7.7, and uranium concentrations between 175 and 300 μg/L. Removals greater than 96 percent were achieved at bed volumes treated between 5,980 and 34,500. Hathaway (1983) also conducted column tests to evaluate the uranium removal capabilities of two AX mini-columns. The results showed a consistent 63 percent removal of an influent uranium concentration of 204 pCi/L (0.3 mg/L) after treating 28,000 bed volumes. EPA (1982) reported 99 percent uranium removal after 48 bed volumes for a mini-column test at an influent concentration of 40 pCi/L (0.06 mg/L).

Jelinek and Correll (1987) evaluated AX using Donex 21K, Ionac A641, and Donex SBR-P resins at two sites. The influent uranium concentrations at one site ranged from 86 pCi/L to 120 pCi/L, and 13 pCi/L to 18 pCi/L at the other. The study showed that both Donex 21K and Ionac A641 resins produced superior results with over 90 percent uranium removal while treating larger bed volumes. A second study was conducted by Jelinek and Correll (1987) utilizing small AX systems treating influent water containing 22 μg/L to 104 μg/L uranium, 166 mg/L to 1200 mg/L total dissolved solids (TDS), and 5 mg/L to 408 mg/L sulfate. This study demonstrated that AX, despite varying raw water qualities, can remove high percentages of uranium.

Studies of uranium removal by ion exchange conducted at Oak Ridge National Laboratory (Lee et al., 1982; Lee and Bondietti, 1983) included both cation and anion exchange resins. Although not as effective as AX, the CX process was able to remove consistently 70 percent of the uranium contamination in the pond waters. The best removals were accomplished using the sodium-form resin at a low sample pH (5.6 to 4.0). Although the authors concluded that uranium removal by CX is probably not practical for drinking water, when CX is implemented for other contaminants (e.g., radium), reasonable uranium removals can also be achieved under the right conditions.

Ion exchange processes are readily adaptable to small treatment plants (NRC, 1996). An IX system serving a population of around 400 has been used for uranium removal in the Blue Mountain subdivision near Denver, Colorado. The source water uranium level has been as high as 135 pCi/L. The IX system produces finished water with uranium levels of 1.5 pCi/L (up to 99 percent removal)

6.3 DESIGN CRITERIA

The major design criteria and assumptions used to estimate costs for enhanced coagulation treatment systems are summarized below. These criteria were based upon the April 1999 Radionuclides T&C document, the November 1999 Arsenic T&C documents and the cost models used to estimate treatment costs: (1) the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993) for small systems; (2) the Water Model (Culp/Wesner/Culp, 1984) for intermediate systems; and (3) the W/W Cost Model (Culp/Wesner/Culp, 1994) for large systems. The VSS and Water Models assume package treatment plants are available. Details of the design criteria can be found in these documents.

Anion Exchange

- Ion Exchange Bed: Sized on the basis of hydraulic considerations. The regeneration frequency of the bed is determined by the NRC limit of 3000 pCi/L on the uranium concentration in wastewater being disposed to a sanitary sewer. The number of bed volumes (BV) before regeneration is estimated to be approximately 300 bed volumes. The total regeneration time required is 50 minutes. In-place resin costs of $70/cubic foot are utilized. NaCl is used as the regenerant, at a cost of $99/ton.

Cation Exchange

- Ion Exchange Bed: Sodium form of CX resin is used at a capacity of 20 Kgr $(CaCO_3)/ft^3$. The total regeneration time required is 54 minutes. A 6-ft bed depth is utilized, with tanks sized for up to 80% resin expansion during backwash. In-place resin costs of $125/cubic foot are utilized. NaCl is used as the regenerant, at a cost of $99/ton. Regeneration facilities are sized on the basis of 150 bed volumes treated before regeneration and a regnerant requirement of 0.275 lb NaCl/kg of exchange capacity.

6.4 TREATMENT COSTS

The treatment costs presented in this section are based on the design criteria provided in section 6.3 above, using the cost models described in Section 3.2. Figures 6-1 and 6-2 represent the anion exchange capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide, as shown in Table 6-1. Figures 6-3 and 6-4 represent the cation exchange capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide groups, as shown in Table 6-2.

Table 6-1

Anion exchange

Radionuclides maximum removal percentages

Radionuclide group	Maximum removal percentage (%)
Radium	NA
Uranium	95
Polonium	70
Lead	NA
Alpha emitters	NA
Beta emitters	90

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

Table 6-2

Cation exchange

Radionuclides maximum removal percentages

Radionuclide group	Maximum removal percentage (%)
Radium	80
Uranium	70
Polonium	NA
Lead	NA
Alpha emitters	80
Beta emitters	NA

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

Curve fitting analysis was conducted on the modeled cost estimates, and include the use of transition flow regions to improve the estimates within the breakpoints between models. The cost curves for IX treatment (both AX and CX) are provided in the remainder of this chapter.

Figure 6-1
Anion Exchange
Capital Costs

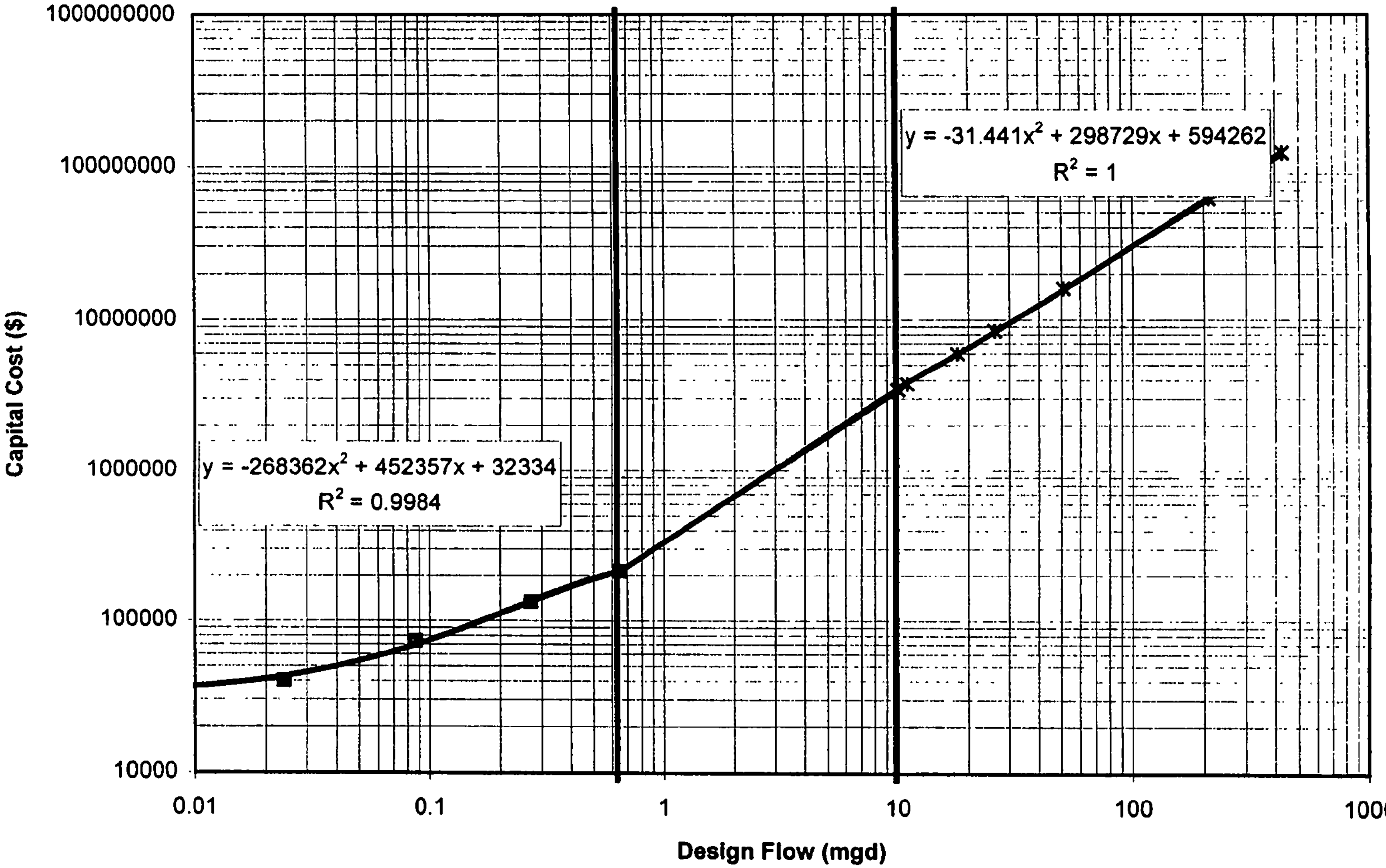


Figure 6-2
Anion Exchange
O&M Costs

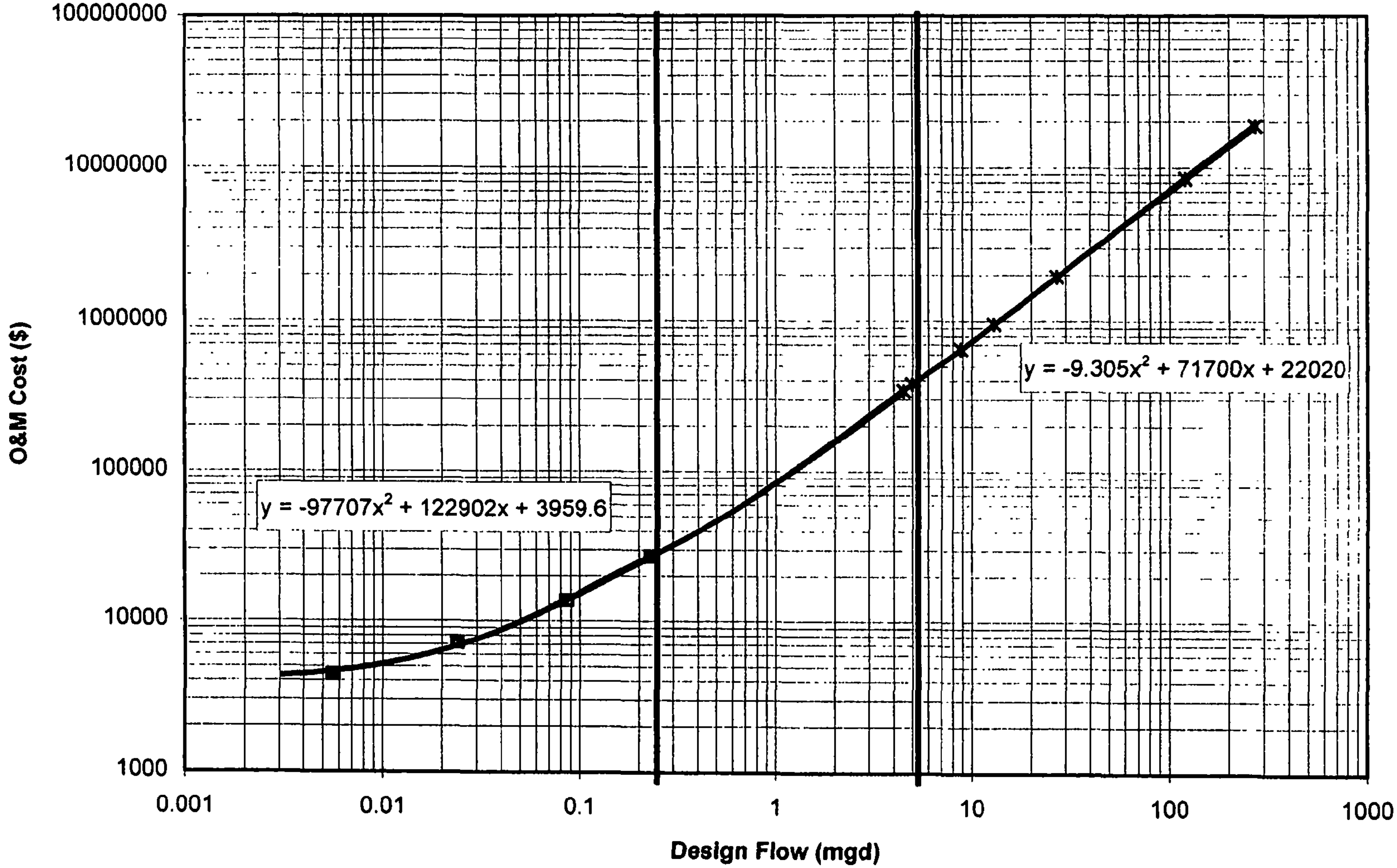


Figure 6-3
Cation Exchange
Capital Costs

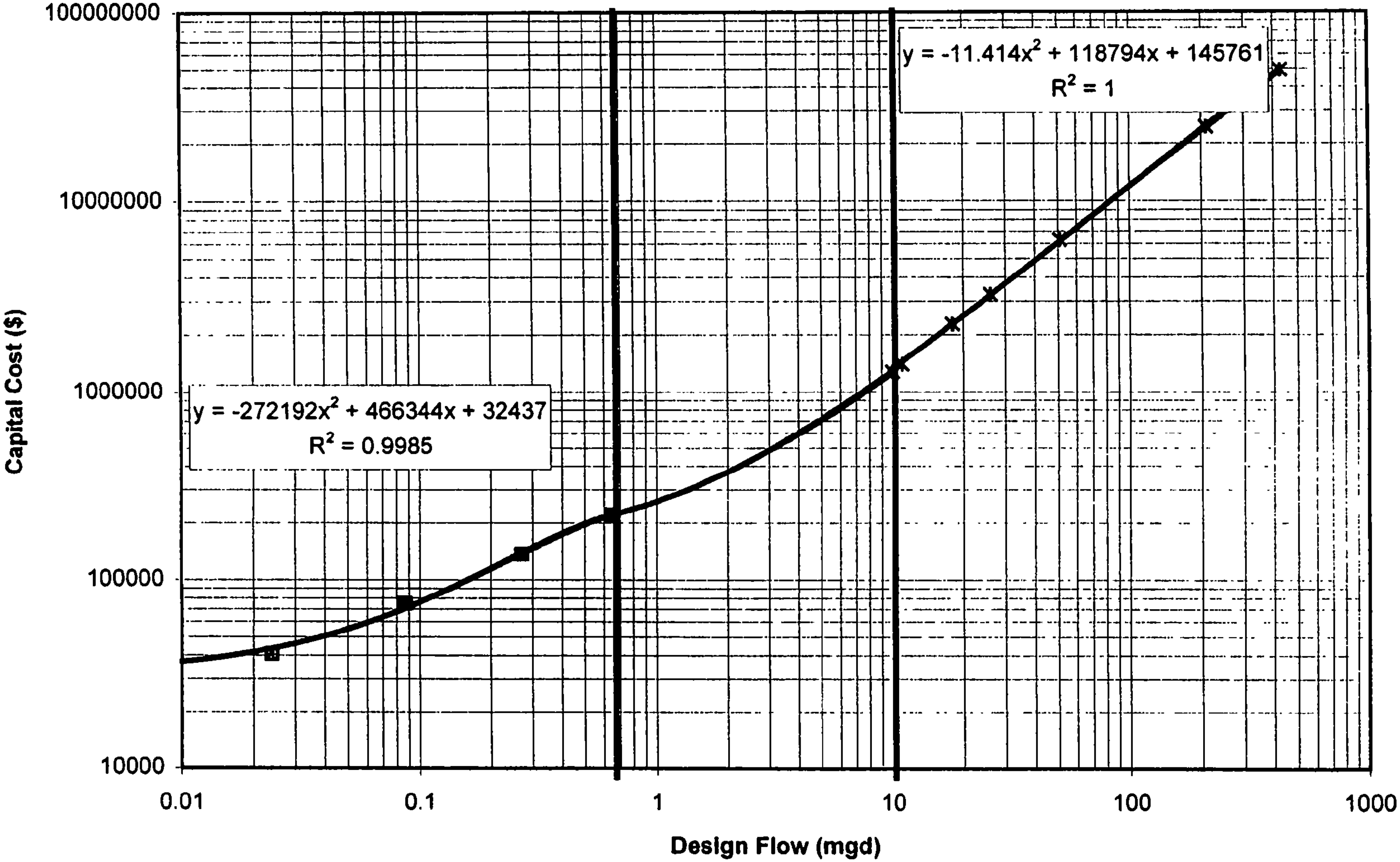
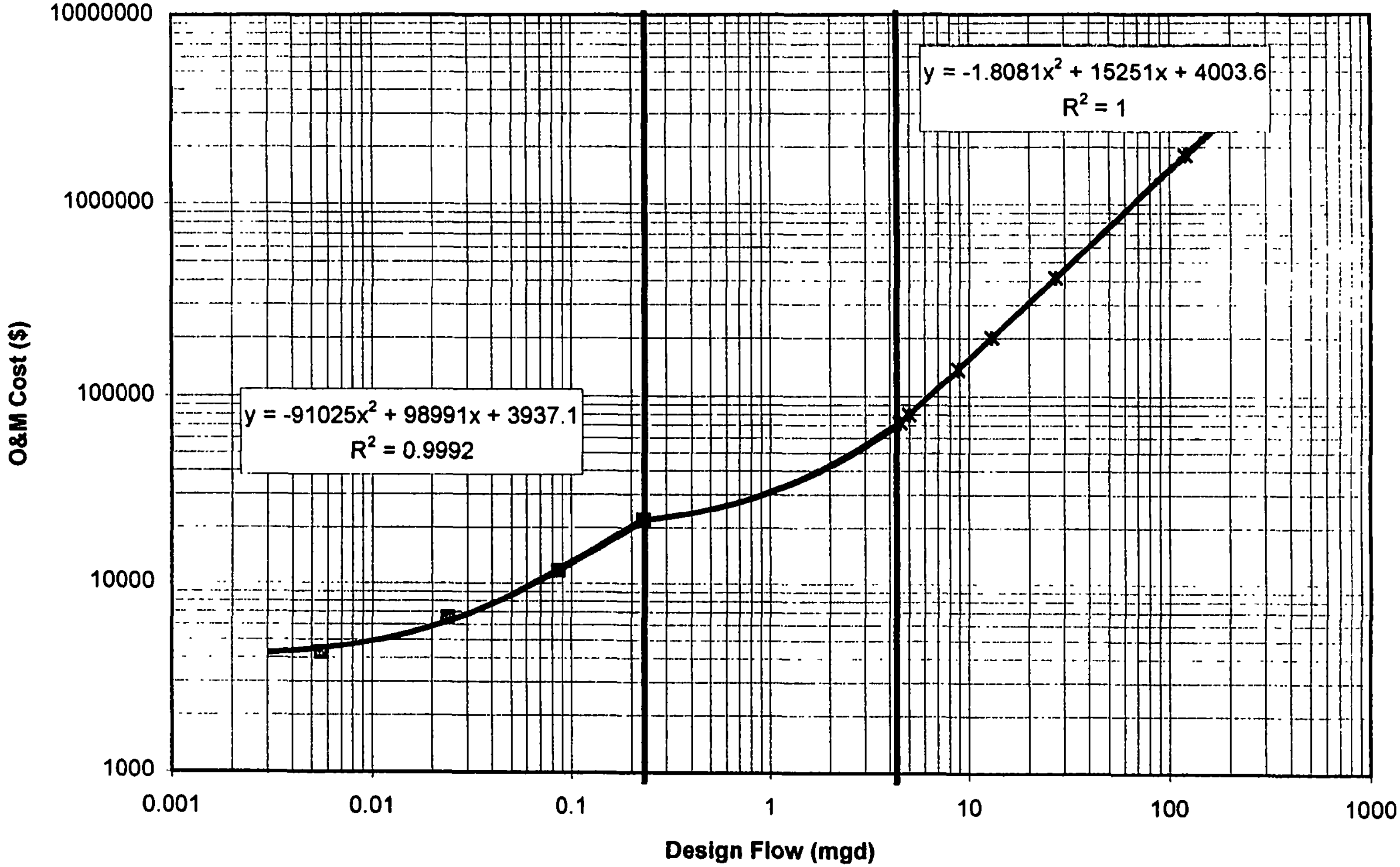


Figure 6-4
Cation Exchange
O&M Costs



7.0 REVERSE OSMOSIS

7.1 PROCESS DESCRIPTION

Reverse osmosis (RO) uses a semipermeable membrane that permits the flow of water through the membrane, while selectively rejecting the passage of dissolved salts in the feed water. Hydraulic pressure on the feed water side produces a pressure gradient that allows water flow across the membrane. This pressure gradient must be greater than the osmotic pressure of the feed water and resistance of the membrane. The portion of feed water that passes through the membrane is referred to as the permeate. The remaining water flushes rejected salts from the membrane surface and is discharged as a concentrate. RO does not selectively remove dissolved contaminants, and is therefore very effective for removing multiple contaminants in one step. RO is adaptable to all size systems and is especially cost effective for small systems.

The performance of an RO system for radionuclide removal depends on a number of factors, including pH, turbidity, iron, and manganese content of the raw water, and membrane type. Pretreatment of the source water may be necessary. The design of a pretreatment system is dependent on the quality and quantity of the feed water source, and may include one or more of the following: pH adjustment, filtration, iron and manganese reduction, and additives for scale prevention. Existing treatment plants may already provide much of the pretreatment required for RO.

The major components of an RO system are provision for prefiltration, including polymer feed system, and provisions for backwashing and backwash water storage (surface water supplies), storage and feed facilities for pH and scale control, reverse osmosis unit, provisions for concentrate or water storage and disposal or treatment; and disinfection.

7.2 APPLICABILITY

Reverse osmosis has been demonstrated to be highly effective in the removal of radioactive contaminants from water. A number of studies have shown that RO is capable of removing 99 percent of the uranium level and over 98 percent of the radium and alpha particle activity level under certain influent conditions. RO also is highly effective (greater than 99 percent) in the removal of radioactive strontium, cesium, and iodine from water (EPA, 1986).

RO systems have little economies of scale and are applicable to both small and large systems. In addition, many RO operations can be automated, reducing both labor and O&M costs.

7.2.1 Radium

In a pilot-scale study of the performance of three different RO modules, Clifford et al. (1988) reported radium removals of more than 90 percent. The three RO membranes were: (1) a thin-film polyamide hollow-fiber membrane; (2) a low pressure composite spiral-wound membrane; and (3) a thin film composite membrane. The first two membranes achieved a 99 percent radium removal at feed pressures of 350 and 125 psi, respectively. The third membrane achieved a 91 percent radium removal at a feed pressure of 70 psi. Hardness removal was also over 90 percent for each of the membranes, and tended to mimic the radium removals. Lauch (1987) summarized the evaluation of several full-scale RO plants with regard to the removal of radium, reporting that each plant provided effective radium removal from drinking water.

7.2.2 Uranium

Huxstep and Sorg (1988) conducted a series of RO pilot studies to assess the effectiveness of RO in removing organics, as well as radionuclides, from drinking water. Four different membranes were tested on a ground water supply with influent uranium concentrations of 300 μg/L. Each membrane removed approximately 99 percent of the uranium from the source water.

Sastri and Ashbrook (1976) reported the results of a study in which an RO unit using a cellulose acetate membrane treated a source water containing uranyl sulfate concentrations of between 100 and 8000 mg/L. The RO unit operated at a feed pressure of 250 psi. The process achieved uranium removals between 98 and 99.4 percent.

7.2.3 Polonium

Based on a treatability study conducted in Maine, over 90 percent removal of polonium (Po) was achieved by RO (EPA, 1991), suggesting that RO is an effective technology for Po-210 removal.

7.2.4 Lead

Based on a study performed by Dixon (1973), the removal of lead (Pb) by RO exceeded 99.5 percent using three types of cellulose membranes. For the purpose of estimating capital and O&M costs, 95 percent removal of lead by RO is assumed.

7.2.5 Gross Alpha Particle Activity

Pilot scale tests were conducted by Flock and Travis (1981) at a defense plant, using a laboratory RO unit containing a spiral wound membrane. Creek water spiked with plutonium was tested at various pH levels. The RO unit achieved 99.9 percent reduction in the level of plutonium.

7.2.6 Beta Particle Activity

A study conducted to determine the ability of RO to remove dissolved strontium (Sr) and iodine (I) from raw water resulted in 90 to 95 percent removal on the first pass (Thomson and Hollandsworth, 1978). The study used two parallel RO units with spiral-wound elements, one polyamide and one cellulose, treating 2400 liters per hour. Radioisotopes in the amount of 2×10^5 pCi were added to the raw water. The study also demonstrated that polyamide membranes removed higher fractions of the radioisotopes than did cellulose acetate membranes.

7.3 DESIGN CRITERIA

The major design criteria and assumptions used to estimate costs for reverse osmosis treatment systems are summarized below. These criteria were taken from the April 1999 Radionuclides T&C document, the November 1999 Arsenic document, and the cost models used to estimate treatment costs: (1) the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993) for small systems; (2) the *Water Model* (Culp/Wesner/Culp, 1984) for intermediate systems; and (3) the *W/W Cost Model* (Culp/Wesner/Culp, 1994) for large systems. Details of the design criteria can be found in these documents.

- Reverse osmosis units: Units are single pass with 400 to 500 psi operating pressure.
- RO package unit (small systems): Spiral wound or hollow fiber cellulose acetate, polyamide, or thin film composite membranes.

- Caustic feed system: Caustic soda is dosed at 100 mg/l; finished water pH is adjusted to 8.

Both the VSS Model and the W/W Cost Model include cost estimation for RO. However, RO spiral-wound membrane module costs have decreased by approximately 50 percent since the models were developed. Accordingly, the membrane module portion of the capital costs and replacement O&M costs was reduced by 50 percent. The W/W Cost Model for RO is only valid up to a capacity of 200 mgd, and no economies of scale were assumed for plants with a capacity larger than the boundary condition of 200 mgd. The model assumes that recovery is 80% for systems of 1 to 10 mgd, and 85% for systems larger than 10 mgd. Costs were adjusted to 75% recovery.

7.4 TREATMENT COSTS

The treatment costs presented in this section are based on the design criteria provided in Section 7.3 above, using the cost models described in Section 3.2. Figures 7-1 and 7-2 represent the capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide groups in question, as shown in Table 7-1.

Table 7-1

Reverse osmosis

Radionuclides maximum removal percentages

Radionuclide group	Maximum removal percentage (%)
Radium	95
Uranium	95
Polonium	90
Lead	95
Alpha emitters	90
Beta emitters	90

Curve fitting analysis was conducted on the modeled cost estimates, and include the use of transition flow regions to improve the estimates within the breakpoints between models.

Figure 7-1
Reverse Osmosis
Capital Costs

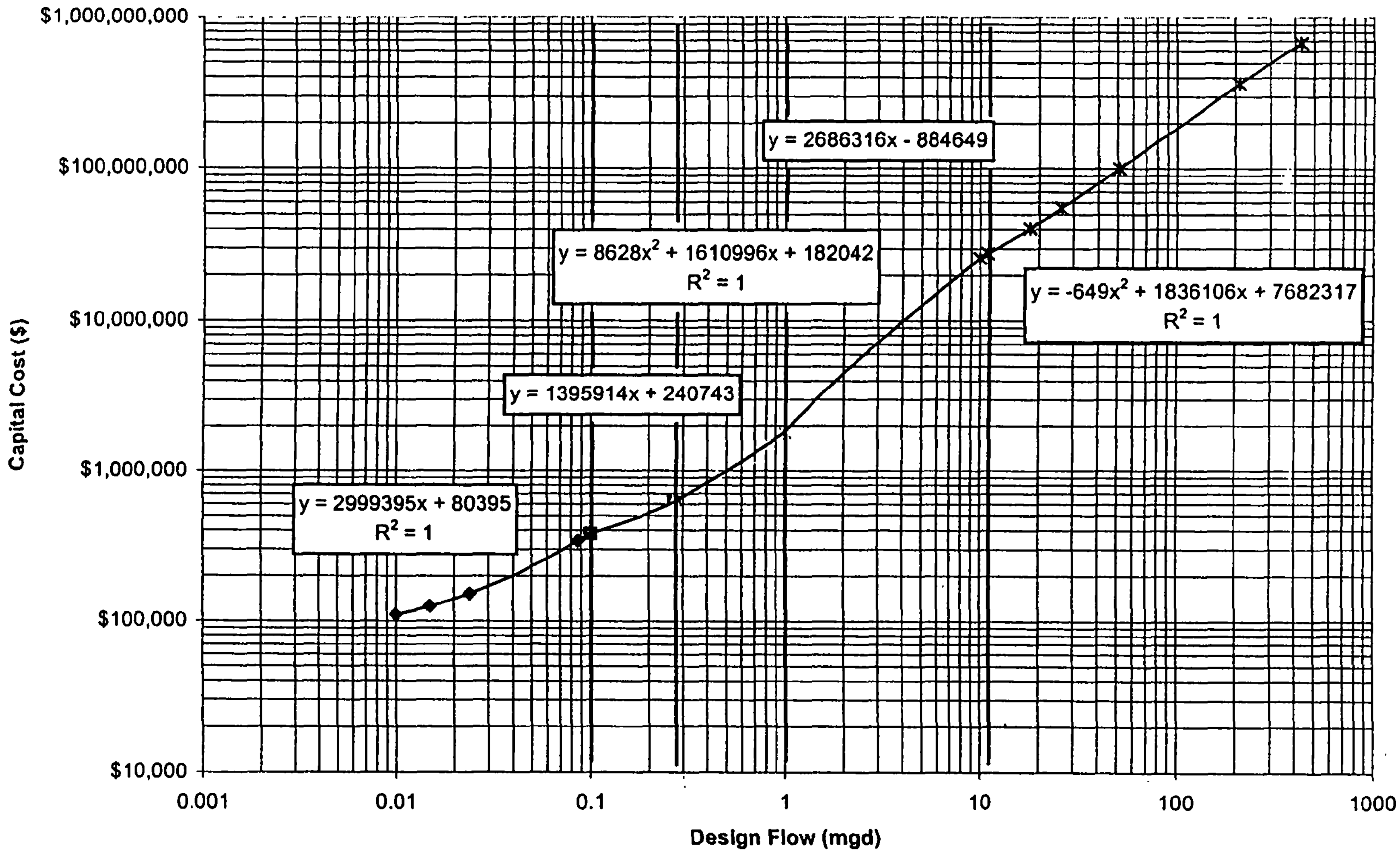
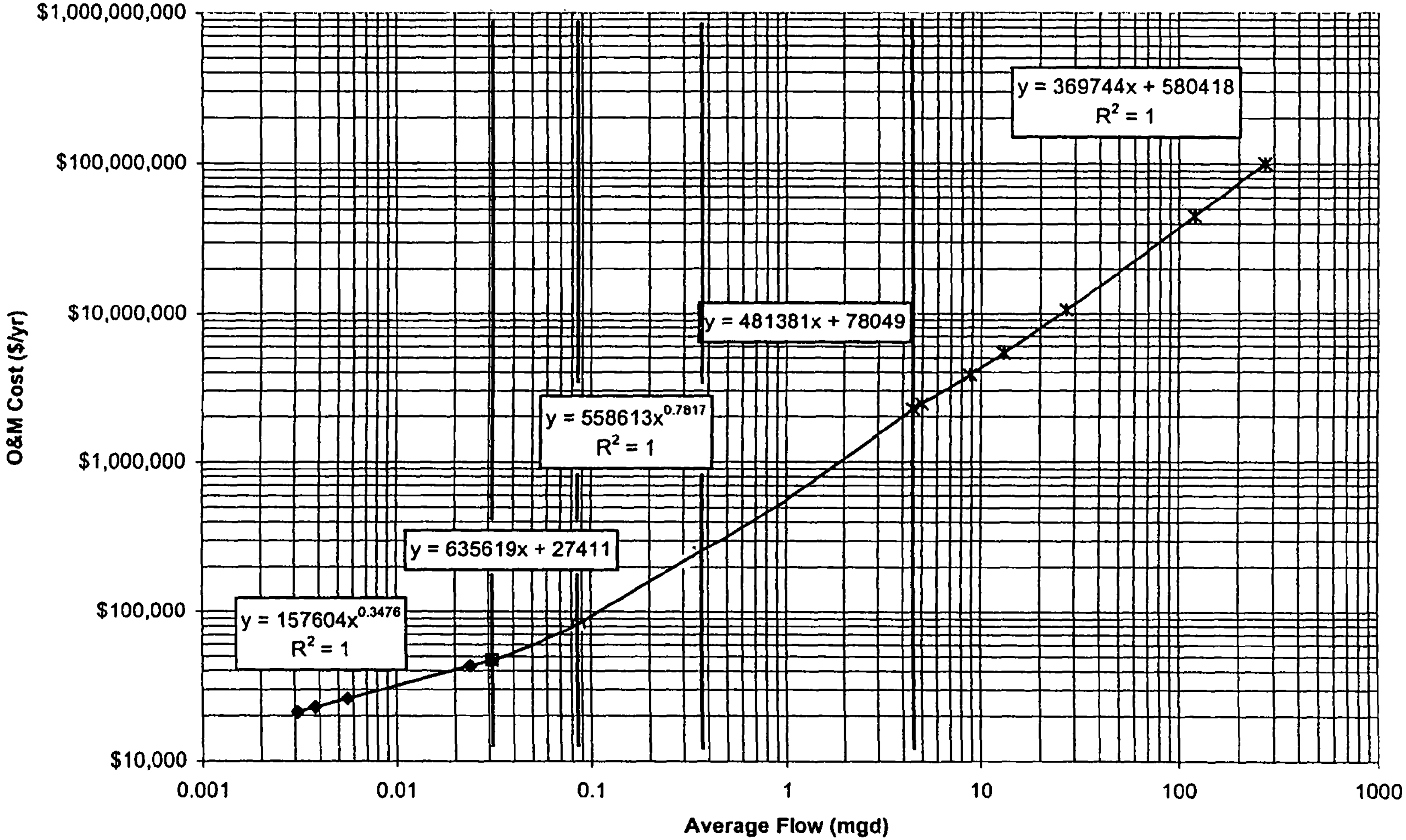


Figure 7-2
Reverse Osmosis
O&M Costs



8.0 ELECTRODIALYSIS REVERSAL

8.1 PROCESS DESCRIPTION

Electrodialysis (ED) is an electrochemical separation process in which ions are transferred through membranes from a less concentrated to a more concentrated solution as a result of the flow of a direct current. The membranes are selectively permeable towards cations and anions. The membranes are arranged in an array, or stack, placed between opposite electrodes, with alternating cation and anion exchange membranes. The movement of the cations or anions is restricted to the direction of the attracting electrodes by membranes of the same charge. This results in alternating sets of compartments containing water with low and high concentrations of the ions. An ED system in which ionic movement is only in one direction is known as unidirectional ED. Control of scaling and fouling material is critical to the operation of unidirectional ED units, and typically requires the use of chemical feed systems, increasing capital and O&M costs.

The electrodialysis reversal (EDR) process is an ED process with periodic reversal of the travel direction of the ions, caused by reversing the polarity of the electrodes. The principal advantage of polarity reversal is a decreased potential for fouling of the membranes, which also minimizes the pretreatment requirements. The polarity of the electrodes is typically reversed three to four times each hour.

EDR is designed specifically for each application based on the desired quantity and quality of product water. Equipment at an EDR plant, in addition to the stack itself, includes feedwater pumps, recycle pumps, and valving including automated motorized valves for feedwater, stream switching, product water diversion, pressure regulation, and electrode stream control. Modern EDR systems are fully automated and require little operator attention beyond data gathering and routine maintenance. For this reason the EDR process is particularly well-suited for small systems.

8.2 APPLICABILITY

Treatability studies have demonstrated that radium and uranium removals of greater than 90 percent can be achieved with EDR under certain circumstances. However, because few EDR studies have been conducted on radionuclide removal, conservative removal assumptions have been made for the radionuclides discussed in this document. The major concern with uranium and radium removal using EDR was the accumulation of contaminants on the membranes, requiring an additional acid wash process for their removal (Clifford and Zhang 1991).

8.2.1 Radium

A treatability study conducted by Clifford and Zhang (1991) demonstrated the effectiveness of EDR for achieving radium removals of up to 94 percent. Radium does not accumulate on the stacks as much as uranium, but periodic acid cleaning was not as effective for removing accumulated radium as it was for uranium. Nineteen percent of the radium removed from the water accumulated on the membrane, and acid washing removed only 5.6 percent of this accumulation.

8.2.2 Uranium

The treatability study conducted by Clifford and Zhang (1991) also showed that up to 95 percent uranium removal can be achieved with EDR. The EDR system was also successful in removing 95, 92, and 87 percent of the conductivity, hardness, and alkalinity, respectively. The principal drawback with this technology was the accumulation of uranium on the stack and the need for acid cleaning to remove it, which is not normally required for most EDR operations. 83 percent of the uranium accumulated on the membrane, and acid cleaning removed 35 percent of this accumulation.

8.2.3 Polonium

Due to the lack of data and case studies for the removal of Po-210 by EDR, capital and O&M cost estimates were not generated.

8.2.4 Lead

Although no specific information was found in the literature on lead removal from drinking water by electrodialysis, the technique should be as effective as RO (Sorg and Logsdon, 1978). Based on a study performed by Mixon (1973), the removal of lead (Pb) by reverse osmosis exceeded 99.5 percent. For the purpose of estimating capital and O&M costs, 95 percent removal of lead by EDR is assumed.

8.2.5 Gross Alpha Particle Activity

Due to the lack of data and case studies for the removal of gross alpha emitters by EDR, capital and O&M cost estimates were not generated.

8.2.6 Beta Particle Activity

Due to the lack of data and case studies for the removal of strontium and iodine by EDR, capital and O&M cost estimates were not generated.

8.5 TREATMENT COSTS

The estimated maximum removal percentages for EDR are summarized in Table 8-1 for each radionuclide group.

While EDR appears to be an effective removal technology, there are operational and cost issues which make application of EDR unlikely. For example, radium and uranium removals were generally good. However, the necessity of a periodic acid wash results in higher treatment costs when compared with traditional EDR operation. These additional costs include: acid solution, acid wash feed system, time and labor associated with acid wash, disposal of membranes as they eventually accumulate undesirable levels of radionuclides, and replacement membranes. Furthermore, when compared with other removal technologie, EDR is less cost effective. For the previous reasons, EDR was not selected as a removal technology for radionuclides, and costs estimates were not provided.

Table 8-1

Electrodialysis reversal

Radionuclides maximum removal percentages

Radionuclide group	**Maximum removal percentage (%)**
Radium	80
Uranium	95
Polonium	NA
Lead	95
Alpha emitters	NA
Beta emitters	NA

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

9.0 GREENSAND FILTRATION

9.1 PROCESS DESCRIPTION

The active material in "greensand" is glauconite, a green, iron-rich, clay-like mineral that has ion exchange properties. Glauconite often occurs in nature as small pellets mixed with other sand particles, giving a green color to the sand. The glauconite is mined, washed, screened, and chemically treated to coat the grains with manganese dioxide, resulting in durable, greenish-black, sand-sized particles.

Impurities in the water are removed through a combination of oxidation, ion exchange, and particle entrapment. As water is passed through the greensand filter, soluble iron and manganese (and other metals) are pulled from solution through ion exchange, and react to form insoluble oxides which are then trapped by the filtration medium.

The greensand is regenerated by washing with a permanganate solution, which re-coats the grains with manganese dioxide. The regeneration can be continuous or intermittent. The latter requires the intermittent passage of potassium permanganate through the greensand bed. The filter medium is also backwashed and rinsed during regeneration. Continuous regeneration involves the constant feeding of potassium permanganate solution and other oxidizing chemicals to the raw water ahead of the filters. The filters are periodically taken off line for backwashing and rinsing. Intermittent regeneration generally allows a higher flow rate and longer runs between regeneration. The major components of a greensand filtration process are the greensand filtration medium, backwash facilities, and potassium permanganate feed systems.

9.2 APPLICABILITY

Although greensand filtration is used principally for the removal of iron and manganese from drinking water, the sorptive capacity of radium to manganese dioxide makes greensand filtration a potentially effective technique for the removal of radium. The applicability of this technique to the removal of other radionuclides has not yet been explored.

9.2.1 Radium

Ciccone and Associates (1987) surveyed six small treatment plants in Virginia that use manganese greensand filtration. The plants typically achieved radium removals of 60 percent or higher. The multi-media filter consisted of effective-size layers of anthracite coal, manganese-treated glauconitic greensand, and gravel. The typical system was continuously regenerated by feeding potassium permanganate and chlorine directly to the raw water prior to the contact tank.

Ficek (1996) examined the radium removal ability of greensand filtration in pilot-scale studies. He reported that radium removal efficiencies ranging from 80 to 97 percent were achieved with the addition of 1.26 mg/L of manganese dioxide prior to the multimedia filter. This suggests that an oxidation step may be required for improved radium removal. The water demand for potassium permanganate dictates the time between regeneration, and poses the greatest challenge to the operation of a greensand unit. The greater the potassium permanganate demand due to higher concentrations of iron and manganese, the better the radium removal.

9.2.2 Uranium

Definitive studies on the effects of greensand filtration on the removal of soluble uranium from drinking water have not been conducted.

9.2.3 Polonium

Due to the lack of data and case studies for the removal of Po-210 by greensand filtration, capital and O&M cost estimates were not generated.

9.2.4 Lead

Due to the lack of data and case studies for the removal of lead by greensand filtration, capital and O&M cost estimates were not generated.

9.2.5 Gross Alpha Particle Activity

Definitive studies on the effects of greensand filtration on the removal of soluble plutonium and thorium from drinking water have not been conducted.

9.2.6 Beta Particle Activity

Due to the lack of data and case studies for the removal of iodine by greensand filtration, capital and O&M cost estimates were not generated for this contaminant. However, data collected by the Oak Ridge National Laboratory indicate up to 99.8 percent removal of strontium by greensand filtration (Lassovszky and Hathaway, 1983).

9.3 DESIGN CRITERIA

The major design criteria and assumptions used to estimate costs for greensand filtration treatment systems are summarized below. These criteria were taken from the April 1999 Radionuclides T&C document, the November 1999 Arsenic, and the cost models used to estimate treatment costs: (1) the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie, 1993) for small systems; (2) the *Water Model* (Culp/Wesner/Culp, 1984) for intermediate systems; and (3) the *W/W Cost Model* (Culp/Wesner/Culp, 1994) for large systems. Details of the design criteria can be found in these documents. Part of these criteria are also based upon vendor supplied data.

- Potassium permanganate dosage: $KMnO_4$ 10 mg/l.
- Filtration rate: 4 gpm/ft^2.

9.4 TREATMENT COST

The treatment costs presented in this section are based on the design criteria provided in Section 9.3 above. Figures 9-1 and 9-2 represent the capital and O&M costs estimates associated with the maximum removal percentage of each of the radionuclide groups in question, as shown in Table 9-1.

Table 9-1

Greeensand filtration

Radionuclides maximum removal percentages

Radionuclide group	Maximum removal percentage (%)
Radium	70
Uranium	NA
Polonium	NA
Lead	NA
Alpha emitters	NA
Beta emitters	NA

NA: This technology is either unsuitable, or has been insufficiently evaluated as to provide a maximum removal percentage.

Curve fitting analysis was conducted on the modeled cost estimates, and includes the use of transition flow regions to improve the estimates within the breakpoints between models.

Figure 9-1
Greensand Filtration
Capital Costs

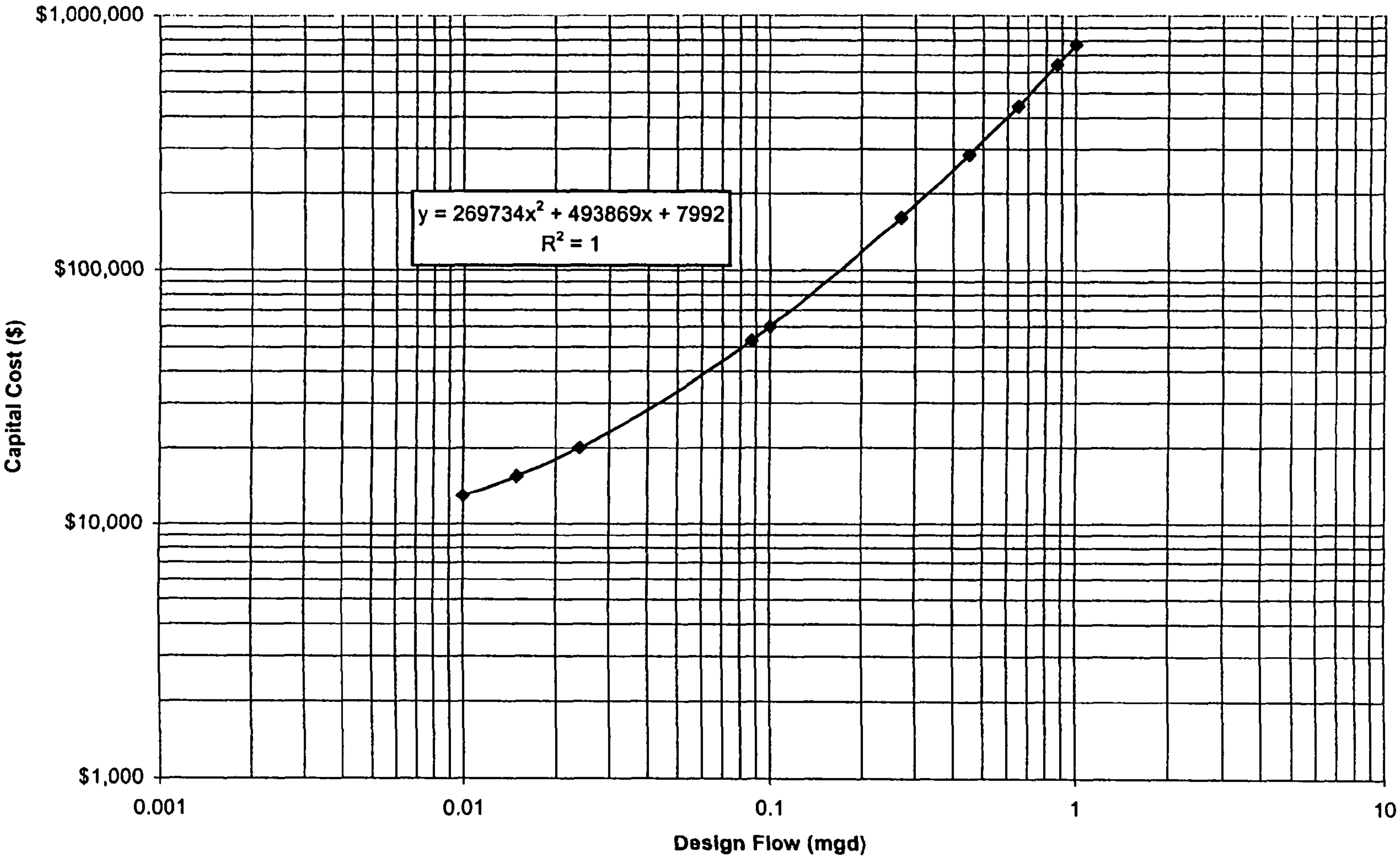
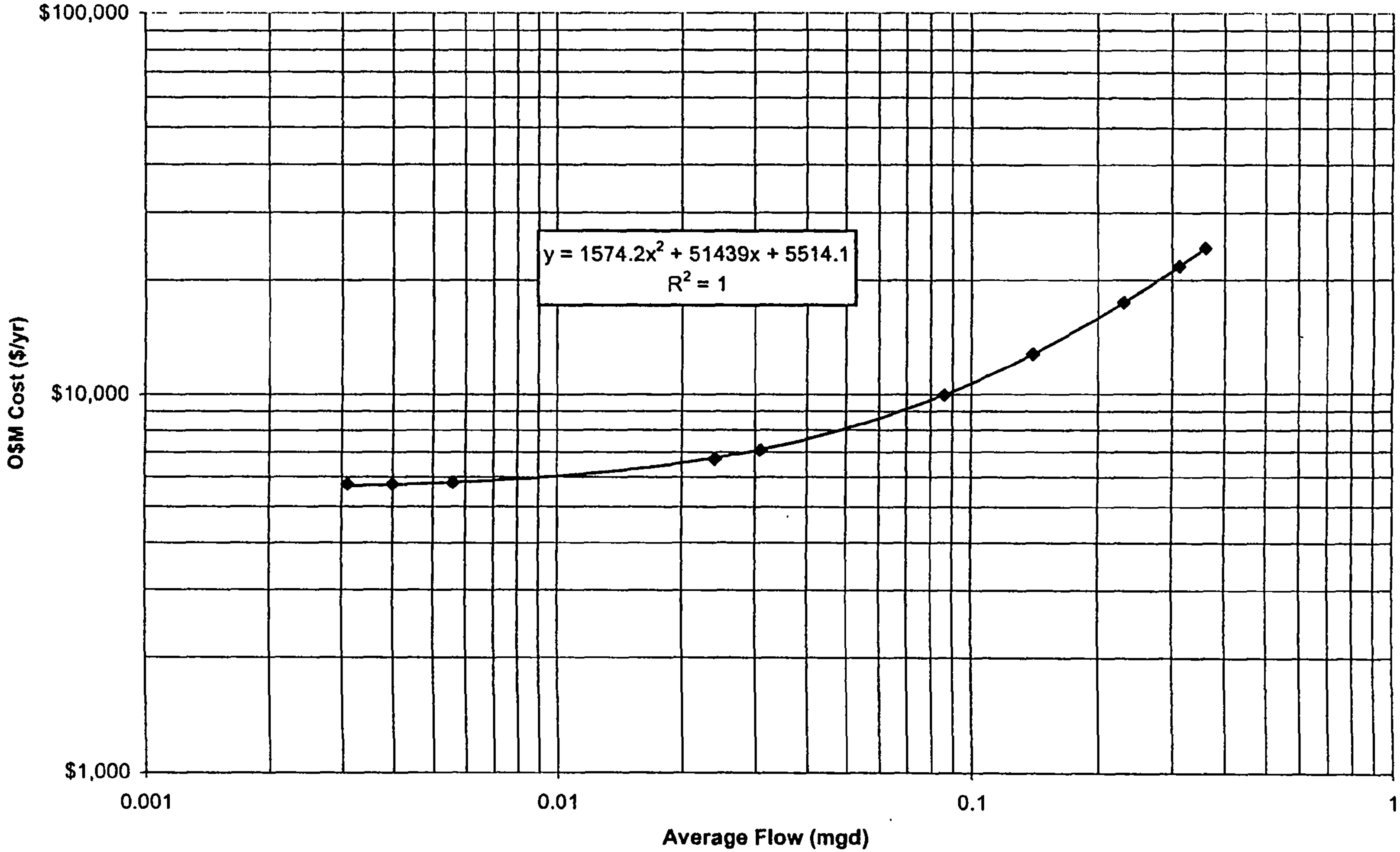


Figure 9-2
Greensand Filtration
O&M Costs



10.0 ACTIVATED ALUMINA

10.1 PROCESS DESCRIPTION

Activated alumina (AA) is an inorganic adsorbent that adsorbs specific cations and anions above and below a pH value of 8.2, respectively. The major components of an AA system are activated alumina column, sodium hydroxide and sulfuric acid storage tanks, day tanks and mixing facilities, and finished water storage.

The alumina capacity is the total quantity of ions that can be exchanged per unit of mass or volume of alumina when the bed has become completely exhausted or has reached a selected breakthrough level. Capacity is a function of the composition and concentrations of the feed solutes, ion selectivity, the flow rate through the bed, the amount of regenerant used, temperature, and the desired finished water quality. Pretreatment of the raw water will also affect the alumina capacity. Suspended solids and precipitated iron can clog the AA bed, and prefiltration of the raw water may be required.

Activated alumina exhibits a degree of selectivity. The presence of more strongly adsorbed compounds can decrease the available exchange capacity for the specific contaminant to be removed (Clifford 1990). If the alumina is operated beyond its exhaustion point for a specific contaminant, compounds with a higher affinity for AA can displace this contaminant from the alumina, and the column effluent will contain a higher concentration of the contaminant than the raw water.

In a fixed-bed system, the alumina is regenerated when all the capacity has been exhausted. During regeneration, the bed is backwashed, regenerated, rinsed, neutralized, and placed back in operation. The regeneration cycle consists of an upflow regeneration, an upflow rinse, and a downflow regeneration. Sodium hydroxide is the most widely used regenerant. In the downflow regeneration cycle, sulfuric acid is used to adjust the pH of the effluent to about 5.5.

10.2 APPLICABILITY

AA is most commonly applied to fluoride removal, but has also been used to remove arsenic and selenium from drinking water. Limited studies have been conducted demonstrating the potential of AA for the removal of uranium, selenium, beryllium, and thallium. Bench scale tests (Sorg, 1988) demonstrated uranium removals of more than 99 percent using AA, with an average of 1600 BVs treated prior to breakthrough. The applicability of AA to removals of other radionuclides has not been studied. Therefore, only AA for uranium removal is considered in this chapter, and the maximum achievable uranium removal is assumed to be 95 percent.

10.3 TREATMENT COST

Although bench studies indicate AA may be an effective removal technology (e.g. for uranium), the data are inconclusive. AA is presented in this document as a possible treatment option, however the scarcity of data makes it inappropriate for inclusion as a compliance technology at this time. For this reason, costs estimates are not provided.

11.0 POINT-OF-USE / POINT-OF-ENTRY

11.1 INTRODUCTION

Centralized treatment is not always a feasible treatment option, for example, in areas where each home has a private well or centralized treatment is cost prohibitive. It is estimated that more than 20 million households in the U.S. draw water from private wells (DeSilva, 1996). In these instances, point-of-entry (POE) and point-of-use (POU) treatment options may be acceptable treatment alternatives. POE and POU systems offer ease of installation, simplify operation and maintenance, and generally have lower capital costs (Fox, 1989). These systems may also reduce engineering, legal and other fees typically associated with centralized treatment options. Use of POE and POU systems does not reduce the need for a well-maintained water distribution system. In fact, increased monitoring may be necessary to ensure that the treatment units are operating properly. Other potential disadvantages associated with POU and POE treatment include: the lack of a required standardized testing and certification program; concern for possible bacterial colonization in the treatment devices; the inability to optimize process operating parameters, such as pH; and increased operation and maintenance costs.

Home water treatment can consist of either whole-house or single faucet treatment. Whole-house, or POE treatment is necessary when exposure to the contaminant by modes other than consumption is a concern. POU treatment is preferred when treated water is needed only for drinking and cooking purposes. POU treatment usually involves single-tap treatment.

Section 1412(b)(4)(E) of the 1996 Safe Drinking Water Act (SDWA) Amendments requires the EPA to issue a list of technologies that achieve compliance with MCLs established under the act. This list must contain technologies for each NPDWR and for each of the small public water systems categories listed below:

- Population of more than 50, but less than 500;
- Population of more than 500, but less than 3,300; and
- Population of more than 3,300, but less than 10,000.

The SDWA identifies POE and POU treatment units as potentially affordable technologies, but stipulates that POE and POU treatment systems "shall be owned, controlled and maintained by the public water system, or by a person under contract with the public water system to ensure proper operation and compliance with the maximum contaminant level or treatment technique and equipped with mechanical warnings to ensure that customers are automatically notified of operational problems."

This chapter discusses three applicable POU and POE treatment techniques for removal of radionuclides from drinking water:

- POU reverse osmosis for radium and uranium removal;
- POU ion exchange for radium and uranium removal; and
- POE cation-exchange for radium removal.

11.2 POU REVERSE OSMOSIS

POU RO devices can remove both radium and uranium, as well as many other inorganic contaminants. The system is usually installed under a kitchen sink and provides water through a separated tap or faucet. Systems include a pre-filter for removal of particulate matter which may cause membrane fouling. A connection to the sink drain is required for brine disposal. Usually, a GAC contactor is installed before the RO system to remove chlorine, and taste- and odor-causing compounds. Water is stored in a pressurized plastic-lined steel chamber. No electricity is required for the process because water pressure delivered to the home is usually sufficient for operation of the RO unit.

11.2.1 Design Criteria and Treatment Costs

Costs for POU RO systems are based upon the costs presented in the 1992 T&C document (EPA, 1992). Costs in the 1992 document are based upon the following criteria:

- Pretreatment is provided with a 5 micron filter;
- The unit includes a membrane unit, a pressure reservoir, a small GAC post-contactor, a special faucet, and all required tubing, fittings, and adaptors;
- Cellulose acetate membranes are used. Pressure is provided by the distribution system;
- O&M costs include collecting samples, replacing the prefilter and GAC contactor, replacing the RO membrane module, and repairs.

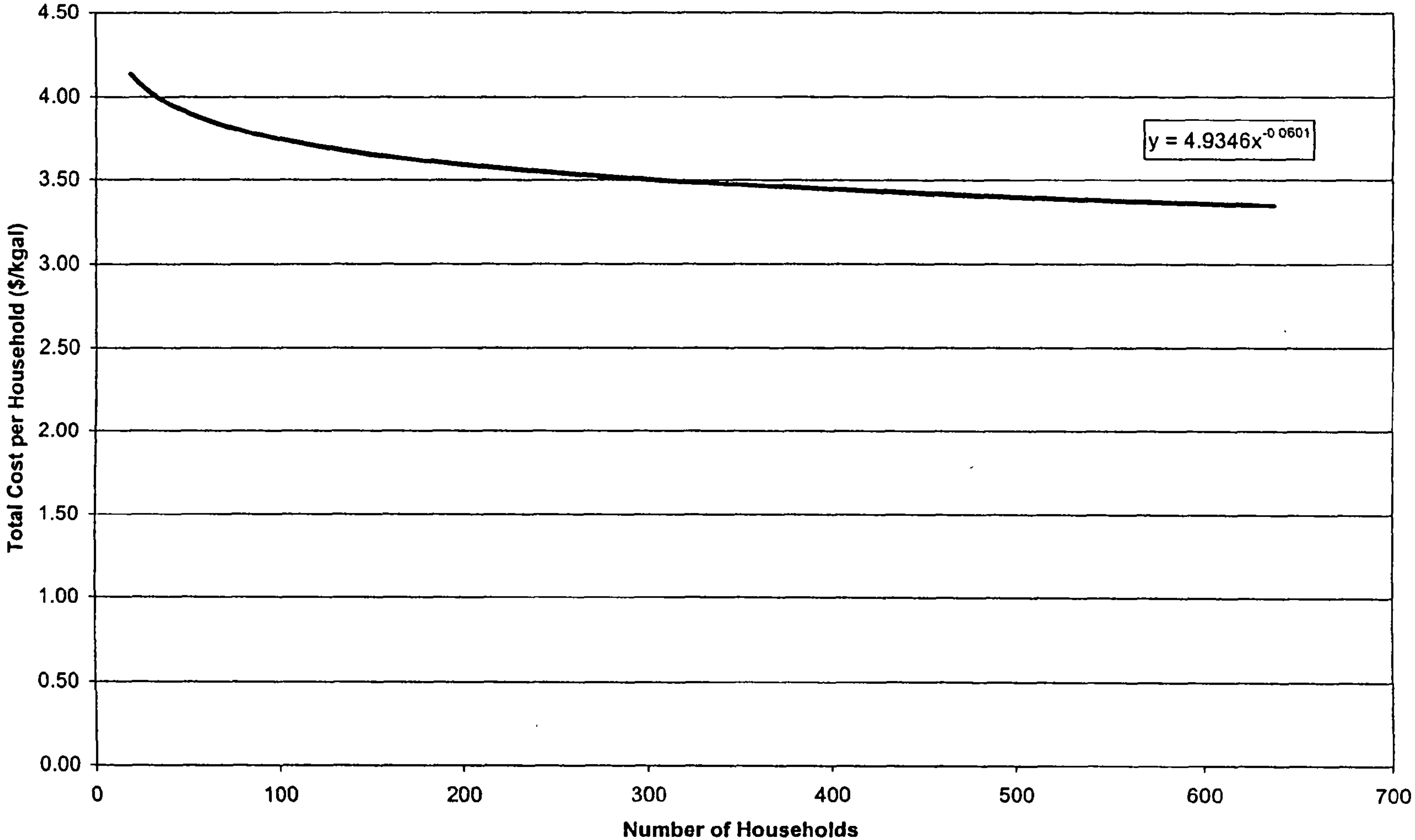
Costs were originally presented on an aggregate, rather than a per household, basis. Costs from the 1992 T&C document were based upon the assumptions in Table 11-1. Costs from the original document were escalated to 1998 dollars using the PPI. The assumptions were then used to calculated costs on a per household basis. Costs are presented in Figure 11-1.

Table 11-1

Cost Assumptions

Median Population	Average Production (gpd)	Units	POU Production Per Unit (gpd)	POE Production Per Unit (gpd)
57	24,000	19	5	1,270
225	87,000	75	5	1,160
750	270,000	250	5	1,080
1,910	650,000	637	5	1,030

FIGURE 11-1
POU Reverse Osmosis for Radium and Uranium Removal



11.3 POU ION EXCHANGE

Desilva (1996) examined POU ion exchange systems as a means for removal of uranium and radium from drinking water. POU ion exchange systems use salt-regenerated cation and anion exchange resins. Uranium is present in water with pH levels of 6.0 and higher as a carbonate complex. As a result, POU strong-base anion exchange is most effective for uranium removal. Strong-acid cation exchange is most effective for removal of radium.

Waste disposal and influent water parameters, including the presence of oxidants, suspended solids, manganese, and iron, must be taken into account when evaluating POU ion exchange as an effective treatment alternative. Further consideration must be given to the corrosive impact of the treated water on the plumbing to avoid copper, iron, or lead leaching into the water.

Monitoring and maintenance of a POU ion exchange system is extremely critical to ensure proper operation. The influent water needs to be tested at least annually. It is also important to periodically monitor the target contaminants and pH in the influent and effluent water and overall resin performance. Certain specific area requirements may call for increased levels of testing and monitoring.

11.3.1 Design Criteria and Treatment Costs

Current literature contains little data on costs associated with POU ion exchange for removal of uranium and radium. *Cost Evaluation of Small System Compliance Options: Point of Use and Point-of-Entry Treatment Units* (Cadmus Group, 1998) presents costs for POU anion exchange units for removal of arsenic, and costs for POU cation exchange units for removal of copper. Because POU treatment units are typically "off-the-shelf," these costs should be similar to POU anion and cation exchange costs for removal of uranium and radium. Figures 11-2 and 11-3 present costs associated with POU anion and cation exchange, respectively.

FIGURE 11-2
POU Anion Exchange for Uranium Removal

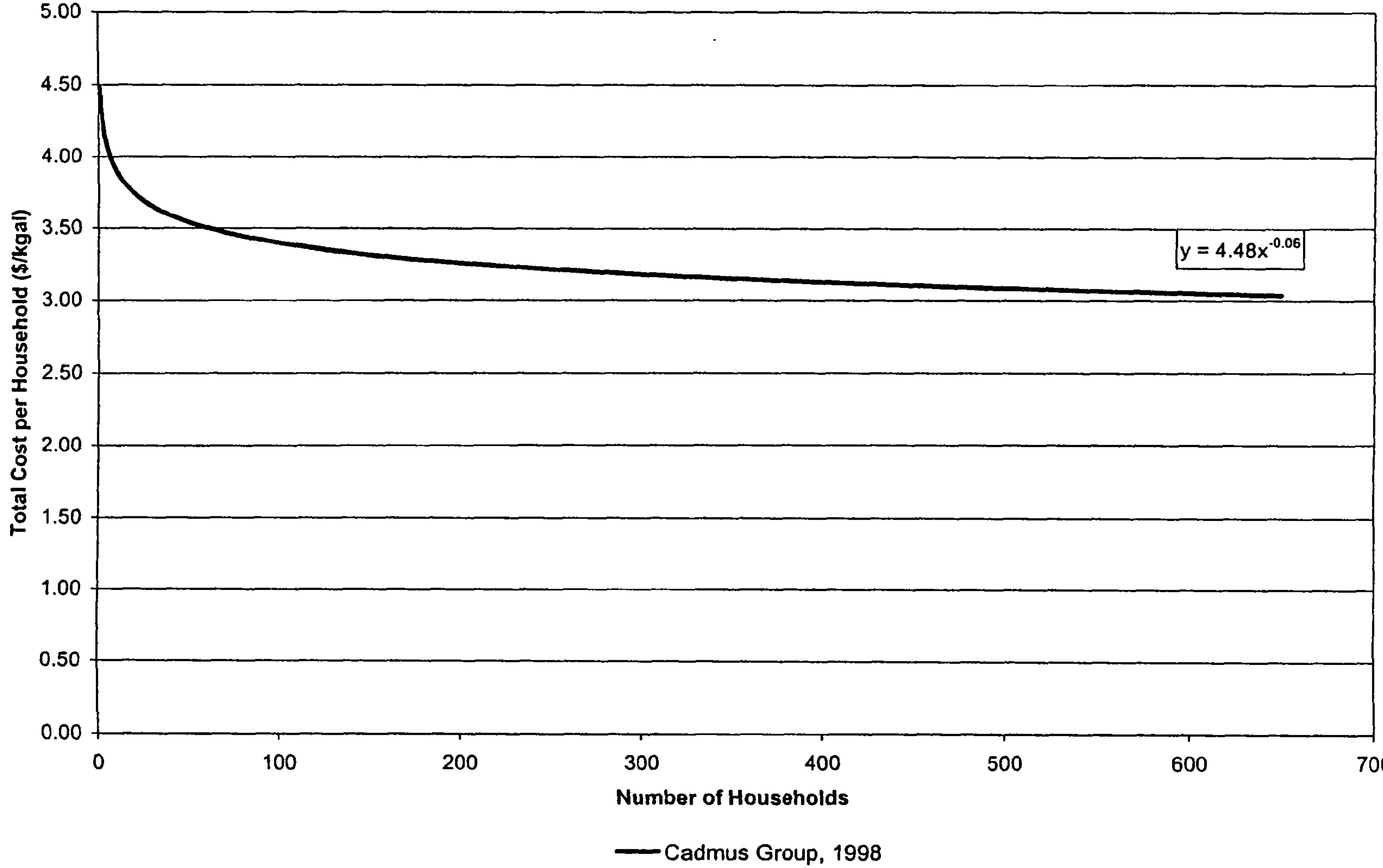
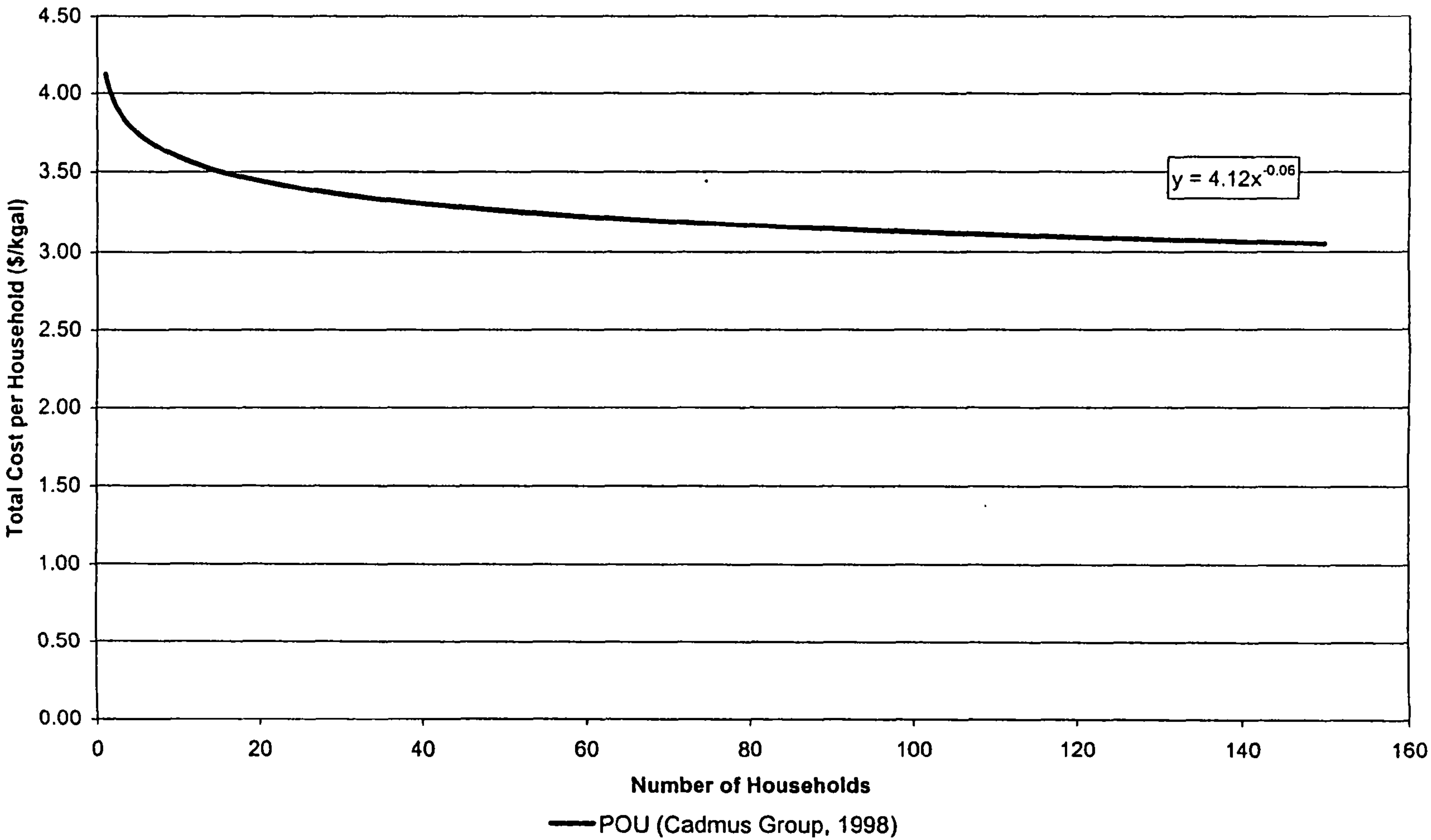


FIGURE 11-3
POU Cation Exchange for Radium Removal



11.4 POE CATION EXCHANGE

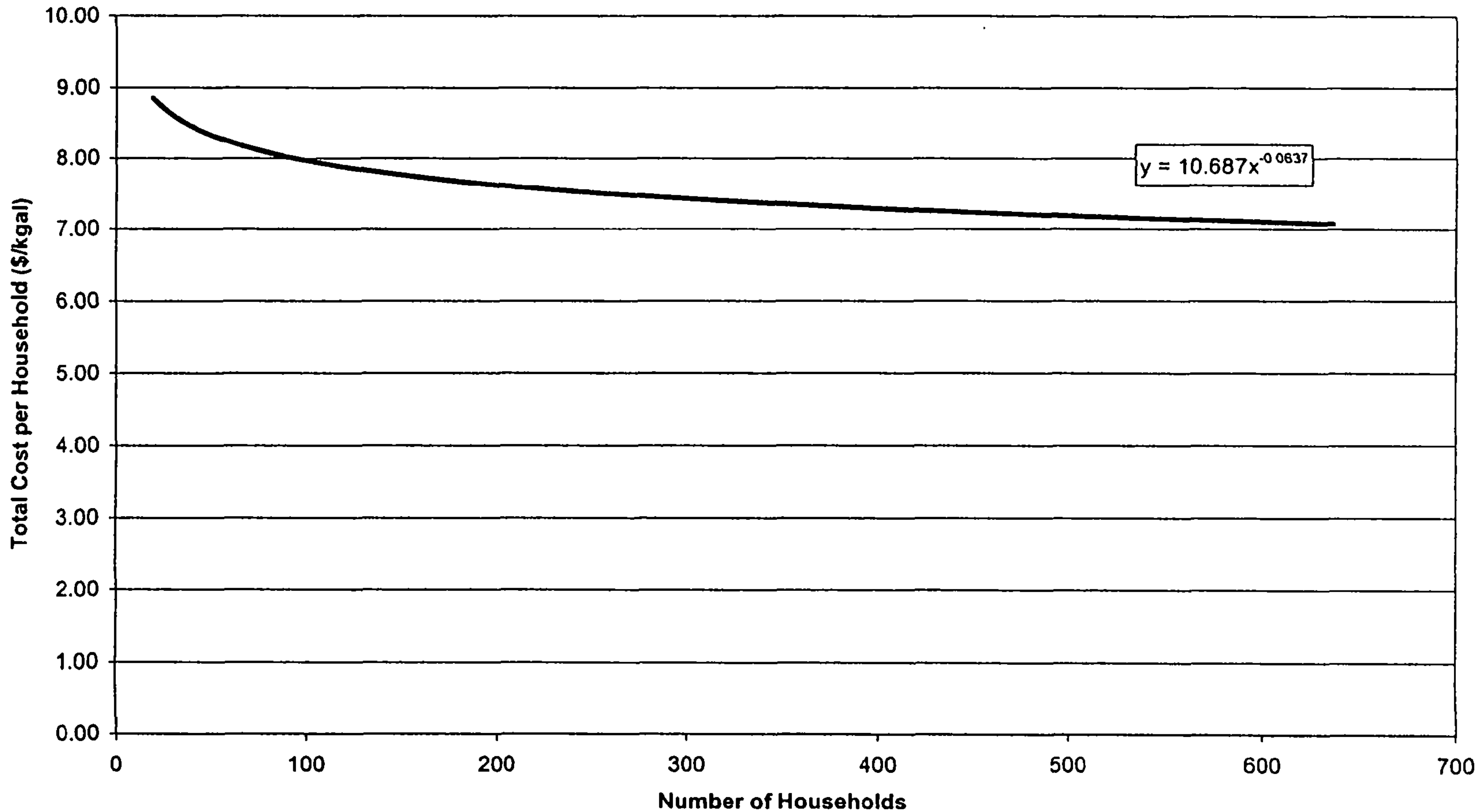
POE cation exchange devices are effective for removal of radium from drinking water. The chemical composition of the water and the concentration of radium impact the actual quantity of water that can be treated prior to regeneration. This may cause variations in actual operation and maintenance costs. No electricity is required to operate the system.

11.4.1 Design Criteria and Technology Costs

The design criteria for cation exchange presented in Section 6.3 were used for development of POE cation exchange system design criteria. It is worth noting that regeneration will occur less frequently than with central treatment. The regeneration frequency will depend upon the quality of the source water and the influent radium concentration. POE cation exchange assumes a sodium-form resin is used at a rate of 10 kg ($CaCO_3$)/ft^3.

Costs were originally presented on an aggregate, rather than a per household, basis. Costs from the 1992 T&C document were based upon the assumptions in Table 11-1. Costs from the original document were escalated to 1998 dollars using the PPI. The assumptions were then used to calculated costs on a per household basis. Costs are presented in Figure 11-4.

FIGURE 11-4
POE Cation Exchange for Radium Removal



12.0 RESIDUALS HANDLING AND DISPOSAL OPTIONS

12.1 INTRODUCTION

Each of the treatment technologies presented in this document will produce residuals, either solid or liquid streams, containing elevated levels of radionuclides. It is the purpose of this chapter to present the characteristics of the waste generated by each of the treatment technologies and discuss appropriate handling and disposal options. Costs for residuals handling and disposal for selected processes also are presented. References are noted which contain appropriate cost information for other treatment processes.

12.1.1 Factors Affecting Residuals Handling and Disposal Costs

There are a number of factors which can influence capital and O&M costs associated with residuals handling and disposal. Capital costs include equipment, construction, installation, contractor overhead and profit, administrative and legal fees, land, and other miscellaneous costs. The primary factor affecting capital cost is the amount of residuals produced, which is dependent upon the design capacity of the water treatment plant, raw water quality, and the treatment process utilized (e.g. coagulation/filtration vs. lime softening).

The amount of waste generated plays a significant role in determining the handling and disposal method to be utilized. Many handling methods which are suitable for smaller systems are impractical for larger systems because of the significant land requirements. For larger systems that process residuals on-site (as opposed to direct or indirect discharge), mechanical methods are typically used because of the reduced land requirements associated with them.

Operations and maintenance costs include labor, transportation, process materials and chemicals, and maintenance. Many handling and disposal methods require extensive oversight which can be a burden on small water systems. Generally, labor intensive technologies are more suitable to large water systems. Transportation can also play a significant role in determining appropriate handling and disposal options. If off-site disposal requires extensive transportation, alternative disposal methods should be evaluated. Complex handling and disposal methods usually require more maintenance.

12.1.2 Methods for Estimating Residuals Handling and Disposal Costs

Residuals handling and disposal costs can be difficult to estimate. There are a number of factors which affect capital and O&M costs, and disposal costs can be largely regional. EPA has published two manuals for estimating residuals handling and disposal costs: *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993a), and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b). Both present a variety of handling and disposal options, applications and limitations of those technologies, and capital and O&M cost equations.

12.2 RESIDUALS HANDLING OPTIONS

The following information is from the *Small Water System Byproducts Treatment and Disposal Document* (DPRA, 1993a) and *Water System Byproducts Treatment and Disposal Document* (DPRA, 1993b). The information presented is a short summary; more detailed explanations of each residuals handling option are presented in the DPRA documents.

12.2.1 Gravity Thickening

Gravity thickening increases the solids content of filter backwash, sedimentation basin residuals and treatment process sludges. It is generally used as a pre-treatment for mechanical dewatering processes, evaporation ponds, and storage lagoons.

Filter backwash streams are high volume, low solids slurries generated during the cleaning of granular filter media. Backwash volume depends upon the number of filters and cleaning frequency. Typical volumes range from 0.5 to 5 percent of the processed water flow with larger plants creating less backwash per million gallons produced than small systems due to increased plant efficiency (DPRA, 1993a). The solids concentration of backwash water can range between 0.01 and 0.15 percent, compared to coagulation sludges which are typically 0.5 to 2.0 percent (DPRA, 1993a).

When possible, backwash waters are recycled to the treatment process. In gravity thickening, backwash water and sedimentation residuals are fed to a tank where settling occurs naturally. Sludges are withdrawn and further treated for ultimate disposal, and the decant is either recycled or discharged to a surface water or publicly-owned treatment works (POTW). Gravity thickening reduces the quantity of water lost due to backwashing, as well as the total volume of sludge generated (DPRA, 1993a). When recycling is not feasible, backwash waters may be discharged to a surface water or a POTW, or treated by other mechanical or non-mechanical dewatering processes. When backwash slurries cannot be recycled or discharged to a surface water or POTW, they must be treated and disposed.

12.2.2 Chemical Precipitation

Chemical precipitation is applicable to brine waste streams generated by cation exchange and reverse osmosis treatment processes. Anion exchange residuals are generally not treated with chemical precipitation because dissolved sodium, chloride, and sulfate are not readily precipitated by lime (DPRA, 1993a,b). The process involves adding a precipitant (e.g. lime) to the brines in a stirred-reactor vessel, resulting in a conversion of dissolved metals to an insoluble form. A clarifier is then used to separate the suspended solids from the aqueous phase. Flocculation may be used to enhance this process. The supernatant may be discharged to a sanitary sewer or to surface water, or recycled to the head of the plant. Additional dewatering may be required prior to the disposal of clarifier sludge. The process is relatively expensive compared to other handling alternatives, such as evaporation ponds and drying beds.

12.2.3 Mechanical Dewatering

Mechanical dewatering processes include centrifuges, vacuum-assisted dewatering beds, belt filter presses, and plate and frame filter presses (DPRA, 1993a). Such processes generally have high capital (excluding land) and O&M costs compared to similar capacity non-mechanical dewatering processes (e.g., storage lagoons). Due to the high costs, such processes are generally not suitable for application at very small water systems.

Filter presses have been used in industrial processes for years, and their use has been increasing in the water treatment industry over the past several years. These devices have been successfully applied to both lime and alum sludges. Prior to pressure filtration, alum sludges may require the addition of lime to lower the resistance of the sludge to filtration. This is generally done by adjusting the pH to approximately 11. Pre-conditioning with lime also increases the dewatered sludge volume by as much as 20 to 30 percent. Lime sludges can attain final solids concentrations of 40 to 70 percent, while alum sludges may reach 35 to 50 percent total solids. Filter presses require little land, have high capital costs, and are labor intensive (DPRA, 1993a). Capital and O&M costs are generally higher than comparable non-mechanical dewatering alternatives. As a result, pressure filtration is most applicable to larger water systems.

Centrifuges have also been used in the water industry for years. They are capable of producing alum sludges with final solids concentrations of 15 to 30 percent and lime sludges with 65 to 70 percent total solids, based upon an influent solids concentration of 1 to 10 percent. Centrifugation is a continuous process requiring minimal time (8 to 12 minutes) to achieve the optimal sludge solids concentration. Centrifuges have low land requirements and high capital costs. They are more labor intensive than non-mechanical alternatives, but less intensive than filter presses. Again, due to the capital and O&M requirements centrifuges are more suitable for larger water systems.

12.2.4 Evaporation Ponds and Drying Beds

Evaporation ponds and drying beds are non-mechanical dewatering technologies wherein favorable climatic conditions are used to dewater waste brines generated by treatment processes such as reverse osmosis and ion exchange (DPRA, 1993a). Brine waste is discharged to a pond for storage and evaporation. Ponds and drying beds are not generally suitable for alum and lime sludges. Typically, such ponds are designed with large surface areas to allow the sun and wind to effectively evaporate residual water. Size is determined by waste flow and storage capacity requirements.

Evaporation ponds and drying beds are used primarily for brine wastes generated by reverse osmosis and ion exchange processes. Such processes produce large volumes of high TDS waste streams and make mechanical dewatering processes, such as filter presses, impractical. Depending upon the solids concentration of the brine waste stream, intermittent removal of solids may be required. For brines with a total dissolved solid (TDS) content ranging from 15,000 to 35,000 mg/L, solids will accumulate in the pond at a rate of ½ to 1½ inches per year (DPRA, 1993a). When the depth of the solids reaches a predetermined level, flow to the pond is halted and evaporation continues until the solids concentration is suitable for disposal.

Evaporation is an extremely land intensive option requiring shallow basins with large surface areas. This can be an important consideration in densely populated regions. Reverse osmosis produces a very large volume reject stream which increases the land requirement and ultimately construction costs. As a result, evaporation ponds may not be suitable for large water systems utilizing reverse osmosis. Evaporation ponds and drying beds have few operations and maintenance requirements, but are only feasible in regions with favorable climatic conditions, i.e., high temperatures, low humidity, and low precipitation (DPRA, 1993a). Waste streams with low TDS concentrations can allow a pond to operate for several years before solids accumulation warrants removal.

12.2.5 Storage Lagoons

Lagoons are the most common, and often least expensive, method to thicken or dewater treatment sludges; however, they are land intensive (DPRA, 1993a). Lagoons are lined ponds designed to collect and dewater sludge for a predetermined period of time. Dewatering occurs by evaporation and decanting of the supernatant. Lagoon size is determined by the volume of sludge produced and the storage time desired. As with evaporation ponds, when a lagoon reaches the design capacity solids can be removed with heavy equipment and shipped for disposal.

Storage lagoons are best suited for dewatering lime softening process sludges, though they have been applied with some success to coagulation/filtration process sludges. They can operate under a variety of sludge flows and solids concentrations, and do not require chemical conditioning of alum sludges (DPRA, 1993a). Typically, lime sludges enter the lagoon at three percent solids, and can be dewatered to 50 to 60 percent solids, whereas alum sludges enter at one percent solids and can be dewatered to 7 to 15 percent solids (DPRA, 1993a). Alum sludges do not typically dewater well in storage lagoons. When the top layer of sludge is allowed to dry, it hardens, sealing moisture in the layers below. Even after several years, alum sludges may require additional dewatering to achieve the 20 percent solids content required at most landfills (DPRA, 1993a). Further, thickened alum sludges can be difficult to remove from lagoons, and often require dredging or vacuum pumping.

As previously stated, lagooning is a land intensive process with limited applicability in densely populated areas, or areas with limited land availability. Such areas need to compare the cost of regular lagoon cleaning and disposal with land acquisition costs. Lagoons are best suited for areas with favorable climatic conditions, i.e., high temperatures, low humidity and low precipitation. In northern climates, winter freezing can help dehydrate alum sludges.

12.3 DISPOSAL OPTIONS

The following information is from the *Small Water System Byproducts Treatment and Disposal Document* (DPRA, 1993a) and *Water System Byproducts Treatment and Disposal Document* (DPRA, 1993b). The information presented is a short summary; more detailed explanations of each disposal option are presented in the DPRA documents.

12.3.1 Direct Discharge

Direct discharge to a surface water is a common method of disposal for water treatment byproducts. No pretreatment or concentration of the byproduct stream is necessary prior to discharge, and the receiving water dilutes the waste concentration and gradually incorporates the sludge or brine (DPRA, 1993a).

Discharge of liquid residuals containing radionuclides to a surface water will be subject to compliance with the National Pollution Discharge Elimination System (NPDES). EPA has established criteria and guidelines for surface water discharge through the NPDES in 40 CFR 125. NPDES establishes limits based upon a variety of factors, including ambient contaminant levels, low flow condition of the receiving water, and design flow of the proposed discharge. Most NPDES limits for solids discharge are around 30 mg/L.

EPA has established methods for determining water quality criteria under authority of the Clean Water Act (40 CFR 131). These criteria will be used by state regulatory agencies to determine discharge limitations for radionuclides depending upon the classification of the receiving water. The allowable discharge is therefore affected by the ability of the receiving water to assimilate the radionuclides without exceeding the water quality criteria.

The primary cost associated with direct discharge is that of the piping. Accommodations must be made for washout ports to prevent clogging because of sedimentation in pipelines. Valving is necessary to control waste flow in the event of pipe bursts, and pipe must be laid at a sufficient depth to prevent freezing in winter months. Direct discharge requires little oversight, and operator experience and maintenance requirements are minimal. This method has been used to successfully dispose of alum and lime sludges, as well as brine streams generated at reverse osmosis and ion exchange water plants (DPRA, 1993a).

12.3.2 Indirect Discharge

In some cases, water treatment process sludges, slurries, and brines may be discharged to a POTW. This most often occurs when the treatment plant and POTW are under the same management authority. This may require addition of a conveyance system to access the sanitary sewer if an adequate system is not already in place (DPRA, 1993a).

Indirect discharge is a commonly used method of disposal for filter backwash and brine waste streams. Coagulation/filtration and lime softening sludges have also been successfully disposed of in this manner. However, the POTW must be able to handle the increased hydraulic and solids loading. The capacity of the sewer system must also be considered when selecting indirect discharge as a disposal option.

The residuals generated from radionuclide treatment processes will be classified as an industrial waste since it contains contaminants (uranium, radium, etc.) which may impact the POTW. As a result, discharge to a POTW is only acceptable when radionuclide concentrations fall within the established Technically Based Local Limits (TBLL) of the current Industrial Pretreatment Program. The Industrial Pretreatment Program serves to prevent NPDES violations, as well as unacceptable accumulation of contaminants in POTW sludges and biosolids. TBLLs are individually determined for each POTW, and take into account background levels of contamination in the municipal wastewater. TBLLs for radionuclides will typically be limited by the contamination of biosolids rather than effluent limitations or process inhibition.

The primary cost associated with indirect discharge is that of the piping. Accommodations must also be made for washout ports to prevent clogging because of sedimentation in pipelines. Valving is necessary to control waste flow in the event of pipe bursts, and pipe must be laid at a sufficient depth to prevent freezing in winter months. Additional costs associated with indirect discharge may include lift stations, additional piping for access to the sewer system, or other surcharges to accommodate the increased demands on the POTW.

12.4 RESIDUALS CHARACTERISTICS

The *Spreadsheet Program to Ascertain Residual Radionuclide Concentrations* (SPARRC Model) (EPA, 1990) was used to estimate waste volumes and concentrations for each of the treatment technologies presented in this document. These waste volumes were then corroborated, where possible, using waste projections contained in the *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993a) and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b).

12.4.1 Coagulation/Filtration

Residuals generated by coagulation/filtration consist of alum sludges with an average volume of 0.11 percent of the treated water flow rate (DPRA 1993a,b). Residuals generated by direct filtration and in-line filtration will have similar characteristics to those produced by coagulation/filtration. Sludge volumes will be slightly less because of the reduced coagulant dosage. The concentration of uranium in the sludge ranges from 10,000 to 30,000 pCi/L for uranium raw water concentrations in the range of 30 to 50 pCi/L (EPA, 1994). Residuals characteristics were estimated by the SPARRC Model and verified by data reported by DPRA (1993b). Table 12-1 presents typical sludge volumes produced by coagulation/filtration treatment plants. Characteristics are presented for the maximum achievable removal percentage. Volumes for percent removals less than the maximum can be estimated by multiplying the volumes presented in the table by the fraction of the flow treated, which can be calculated using the equation presented in Section 3.3.2.

The following handling and disposal options may be used for coagulation/filtration residuals. Indirect discharge options are subject to the constraints discussed in Section 12.3.2.

- Mechanical Dewatering
- Non-Mechanical Dewatering
- Indirect Discharge

Table 12-1

Coagulation/Filtration Residuals Characteristics

Design Flow (mgd)	Average Flow (mgd)	Solids Production		Waste Production	
		Design (lb/day)	Average (lb/day)	Design (mgd)	Average (mgd)
0.024	0.0056	4	1	0.000048	0.000012
0.087	0.024	14	3	0.00017	0.000036
0.27	0.086	43	12	0.0005	0.00014
0.65	0.23	105	34	0.0013	0.00041
1.8	0.7	291	108	0.0035	0.0013
4.8	2.1	815	351	0.0098	0.0042
11	5	1,773	792	0.0212	0.0095
18	8.8	2,921	1,418	0.0349	0.0017
26	13	4,220	2,105	0.0505	0.0252
51	27	8,277	4,421	0.0991	0.0529
210	120	34,083	19,878	0.4084	0.2381
430	270	69,789	45,261	0.8358	0.5421

12.4.2 Lime Softening

Residuals generated by lime softening are generally sludges with an average volume of 1.2 percent of the design water flow rate (DPRA 1993 a,b). The typical radium concentration in sludge ranges from 1,980 to 2,500 pCi/L (EPA, 1994). Table 12-2 presents estimated residuals volumes, as calculated by the SPARRC Model and verified using data reported by DPRA (1993b). Characteristics are presented for the maximum achievable removal percentage. Volumes for percent removals less than the maximum can be estimated by multiplying the volumes presented in the table by the fraction of the flow treated, which can be calculated using the equation presented in Section 3.3.2.

The following handling and disposal options may be appropriate for lime softening residuals. Use of indirect discharge is subject to the constraints presented in Section 12.3.2.

- Mechanical Dewatering
- Non-Mechanical Dewatering

- Indirect Discharge

Table 12-2

Lime Softening Residuals Characteristics

Design Flow (mgd)	Average Flow (mgd)	Solids Production		Waste Production	
		Design (lb/day)	Average (lb/day)	Design (mgd)	Average (mgd)
0.024	0.0056	98	23	0.00011	0.000026
0.087	0.024	357	98	0.0004	0.00011
0.27	0.086	1,107	335	0.0012	0.00038
0.65	0.23	2,665	940	0.003	0.0011
1.8	0.7	7,381	2,865	0.0083	0.0032
4.8	2.1	19,720	8,622	0.022	0.0097
11	5	45,098	20,486	0.051	0.023
18	8.8	73,808	36,079	0.083	0.041
26	13	106,615	53,307	0.12	0.060
51	27	209,158	110,765	0.23	0.12
210	120	861,218	492,516	0.97	0.55
430	270	1,780,000	1,068,000	2.0	1.2

12.4.3 Ion Exchange Processes

The residuals generated from ion exchange processes are generally brines produced during the regeneration of the ion exchange bed (DPRA, 1993a,b). The byproduct volume from ion exchange ranges from 1.5 to 10 percent of the treated water depending on raw water conditions (e.g., hardness). Table 12-3 presents estimated brine volumes for ion exchange processes. The estimates are based upon average brine production reported by six operating ion exchange water treatment plants (DPRA, 1993a,b). Characteristics are presented for the maximum achievable removal percentage. Volumes for percent removals less than the maximum can be estimated by multiplying the volumes presented in the table by the fraction of the flow treated, which can be calculated using the equation presented in Section 3.3.2.

The following handling and disposal options may be used for ion exchange residuals. Indirect discharge is subject to the limitations presented in Section 12.3.2.

- Evaporation Pond
- Indirect Discharge
- Chemical Precipitation (Cation Exchange Only)
- Direct Discharge

Table 12-3

Ion Exchange Residuals Characteristics

Design Flow (mgd)	Average Flow (mgd)	Brine Production	
		Design (mgd)	Average (mgd)
0.024	0.0056	0.0012	0.0003
0.087	0.024	0.0044	0.0012
0.27	0.086	0.0135	0.0043
0.65	0.23	0.0325	0.0115
1.8	0.7	0.090	0.035
4.8	2.1	0.240	0.105
11	5	0.550	0.250
18	8.8	0.900	0.440
26	13	1.300	0.650
51	27	2.550	1.350
210	120	10.500	6.000
430	270	21.500	13.500

12.4.4 Reverse Osmosis

Residuals generated by reverse osmosis are brines with volumes of reject water ranging from 25 to 50 percent in systems with less than 1 mgd capacity, and 15 to 20 percent for systems with capacities larger than 1 mgd (DPRA, 1993a,b). The concentration of radionuclides in the reject stream is dependent upon the removal efficiency and the influent concentration (EPA, 1994). Table 12-4 presents residuals characteristics as estimated by the SPARRC Model and verified using data reported by DPRA (1993a,b). Characteristics are presented for the maximum achievable removal percentage. Volumes for percent removals less than the maximum can be estimated by multiplying the volumes presented in the table by the fraction of the flow treated, which can be calculated using the equation presented in Section 3.3.2.

Table 12-4

Reverse Osmosis Residuals Characteristics

Design Flow (mgd)	Average Flow (mgd)	Reject Stream Volume	
		Design (mgd)	Average (mgd)
0.024	0.0056	0.011	0.003
0.087	0.024	0.042	0.011
0.27	0.086	0.13	0.042
0.65	0.23	0.32	0.11
1.8	0.7	0.30	0.12
4.8	2.1	0.80	0.35
11	5	1.84	0.84
18	8.8	3.01	1.47
26	13	4.35	2.17
51	27	8.53	4.51
210	120	35.1	20.1
430	270	71.9	45.1

The following handling and disposal options may be used for reverse osmosis residuals. Direct and indirect discharge are subject to the limitations presented in Sections 12.3.1 and 12.3.2.

- Direct Discharge
- Indirect Discharge
- Chemical Precipitation

12.5 DISPOSAL COSTS

The disposal costs presented in this section are based on the residual handling and disposal options presented in Sections 12.2 and 12.3, and on the residuals characteristics presented in Section 12.4. Cost models are from the *Small Water System Byproducts Treatment and Disposal Cost*

Document (DPRA, 1993a) and the *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b).

Costs are estimated for four water treatment processes: (1) coagulation/filtration, (2) lime softening, (3) ion exchange, and (4) reverse osmosis. The disposal options assumed for each of these treatment processes are shown below:

- Coagulation/Filtration:
  - Mechanical dewatering and non-hazardous landfill disposal
  - Non-mechanical dewatering and non-hazardous landfill disposal
  - Non-mechanical dewatering and dewatered sludge land application
  - Liquid sludge land application - sprinkler system
  - Liquid sludge land application - trucking system
- Lime Softening:
  - Mechanical dewatering and non-hazardous landfill disposal
  - Non-mechanical dewatering and non-hazardous landfill disposal
  - Non-mechanical dewatering and dewatered sludge land application
  - Liquid sludge land application - sprinkler system
  - Liquid sludge land application - trucking system
- Ion Exchange:
  - Chemical precipitation
  - Direct discharge
  - Evaporation pond and non-hazardous landfill disposal
  - Discharge to POTW
- Reverse Osmosis:
  - Chemical precipitation
  - Direct discharge
  - Discharge to POTW

The cost estimates are illustrated in Figures 12-1 through 12-42. The assumptions used in these cost estimates include:

- For options involving landfill disposal, 100 percent of the solids are sent to a landfill.
- Ion exchange brine concentration is 25,000 mg/L TSS, based on DPRA (1993a,b) estimates of 15,000 to 35,000 mg/L TSS.
- Land costs are $1,000 per acre for systems less than 1 mgd.
- Land costs are $10,000 per acre for systems greater than 1 mgd.
- For coagulation/filtration, sedimentation basin solids were assumed to be 1%.
- For lime softening, clarifier solids were assumed to be 10%.

Figure 12-1
Mechanical Dewatering and Non-Hazardous Landfill
Coagulation Filtration
Disposal Capital Costs

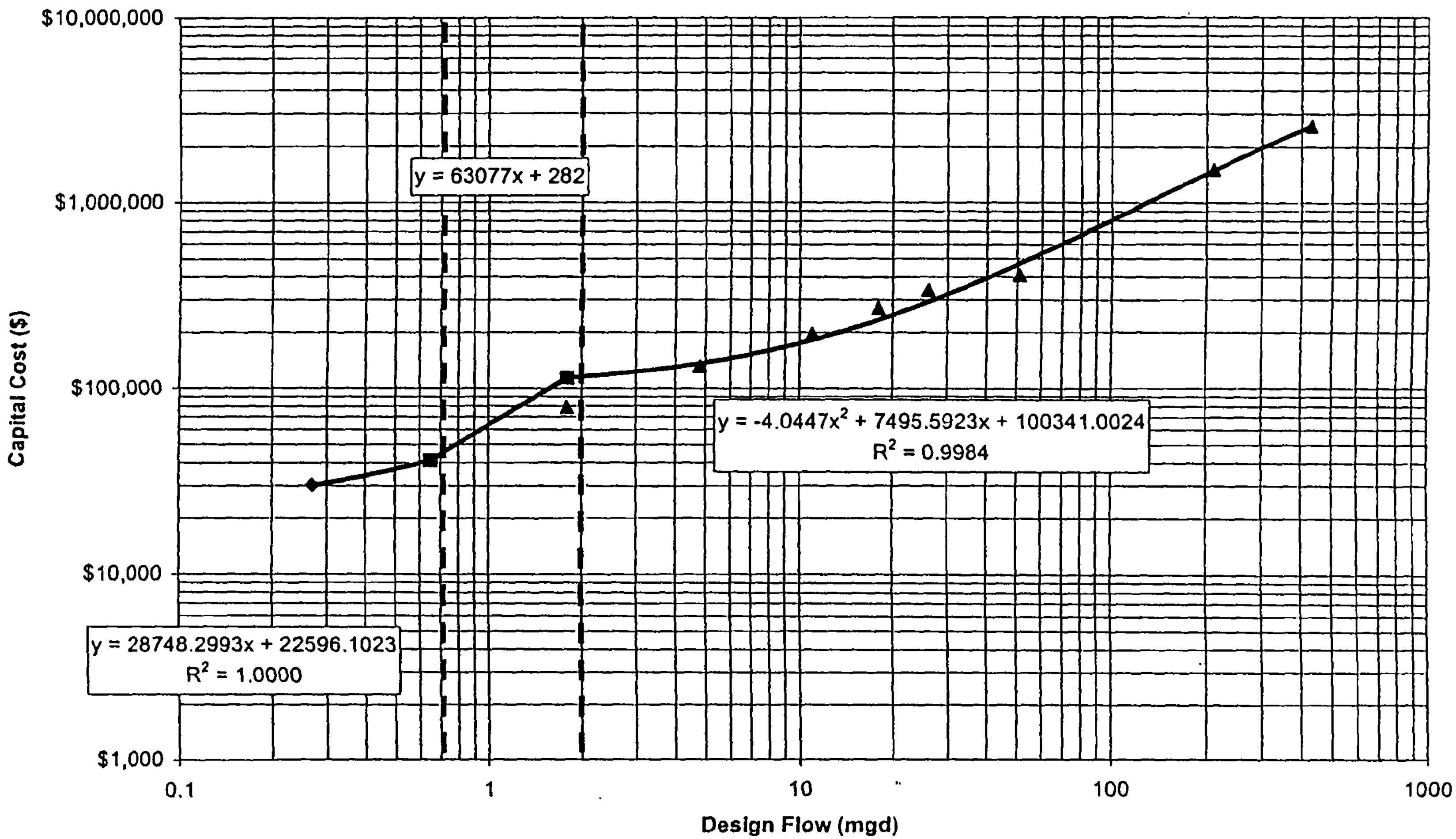


Figure 12-2
Mechanical Dewatering and Non-Hazardous Landfill
Coagulation Filtration
Disposal O&M Costs

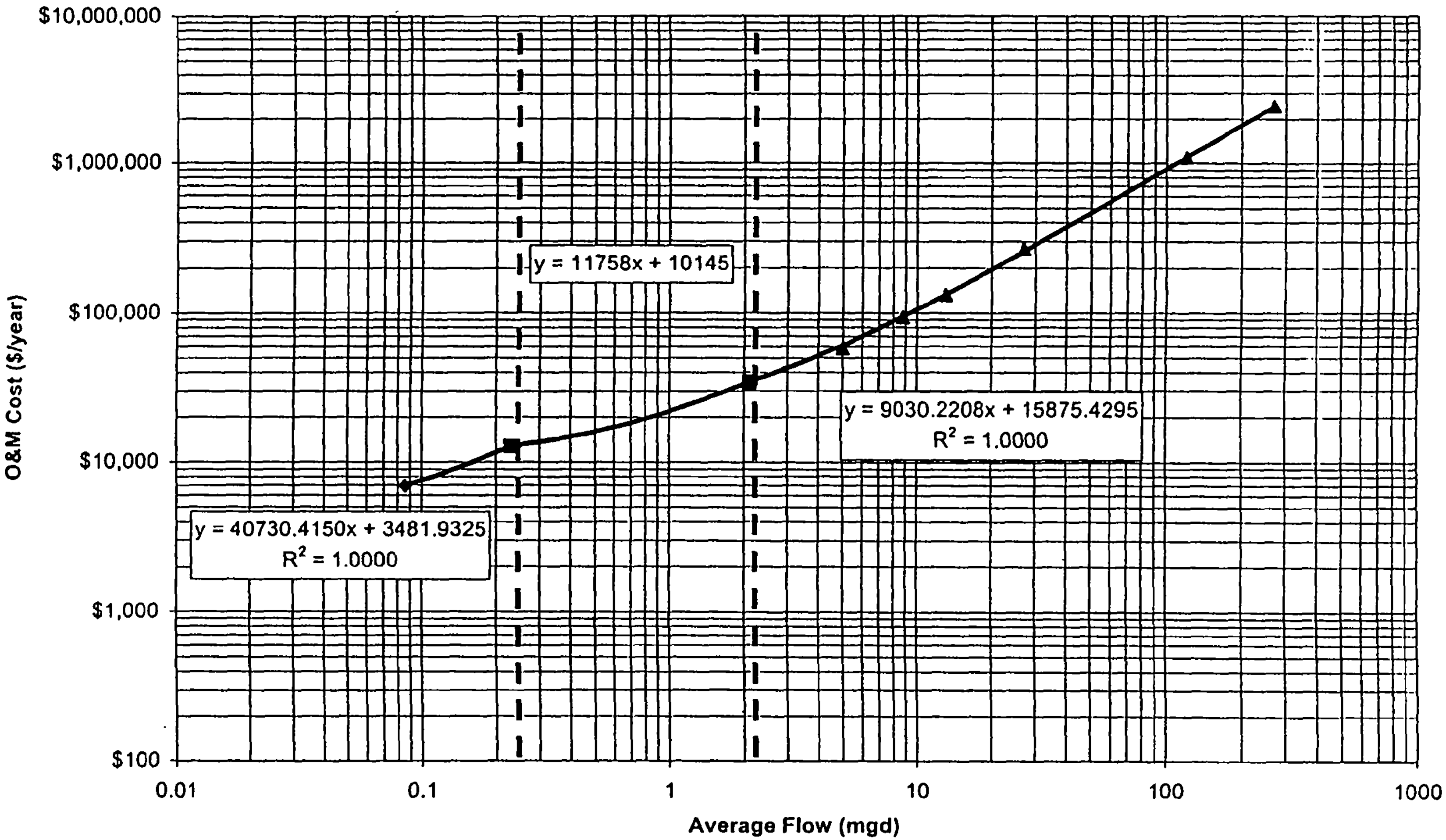


Figure 12-3
Non-Mechanical Dewatering and Non-Hazardous Landfill
Coagulation Filtration
Disposal Capital Costs

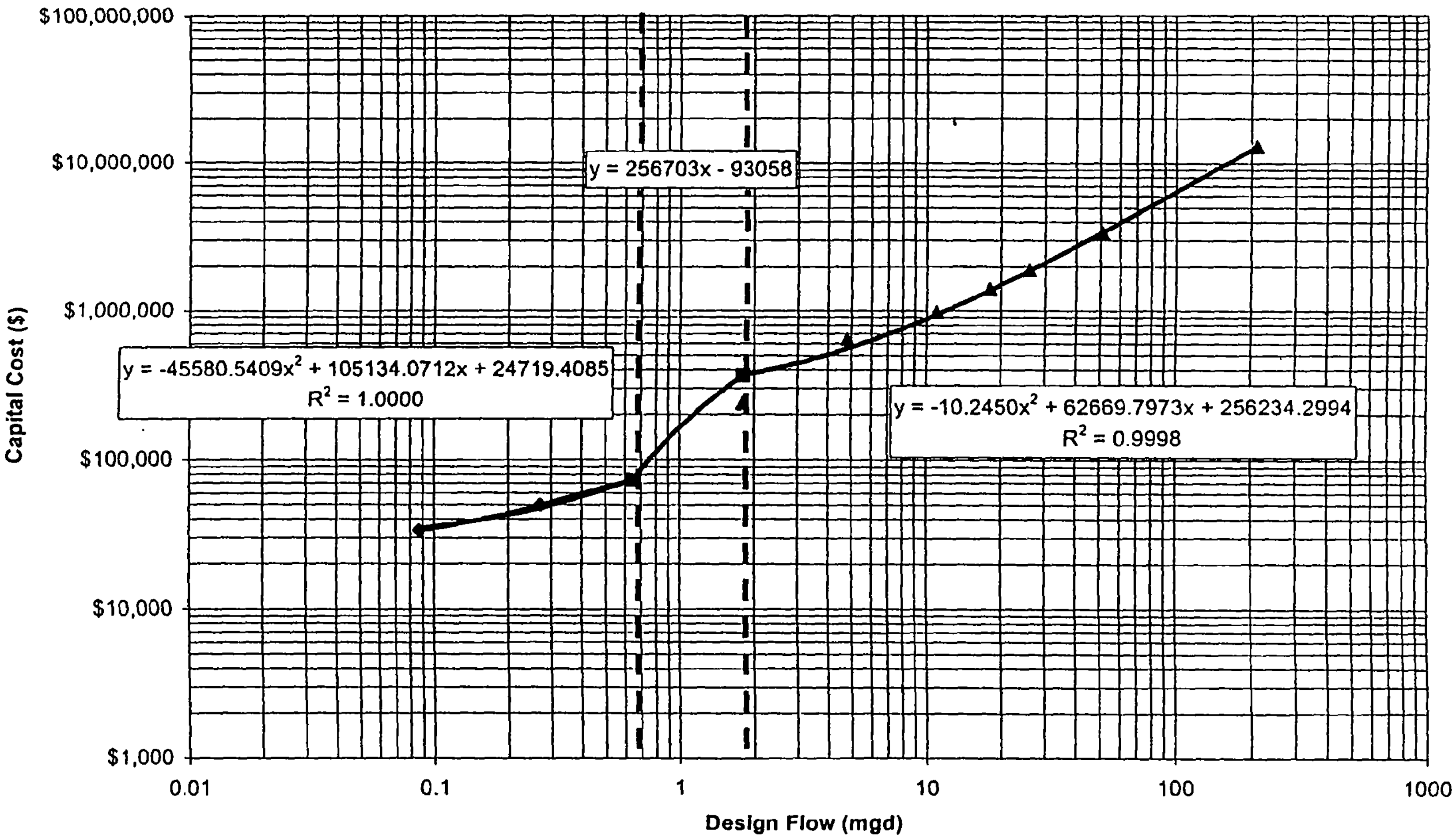


Figure 12-4
Non-Mechanical Dewatering and Non-Hazardous Landfill
Coagulation Filtration
Disposal O&M Costs

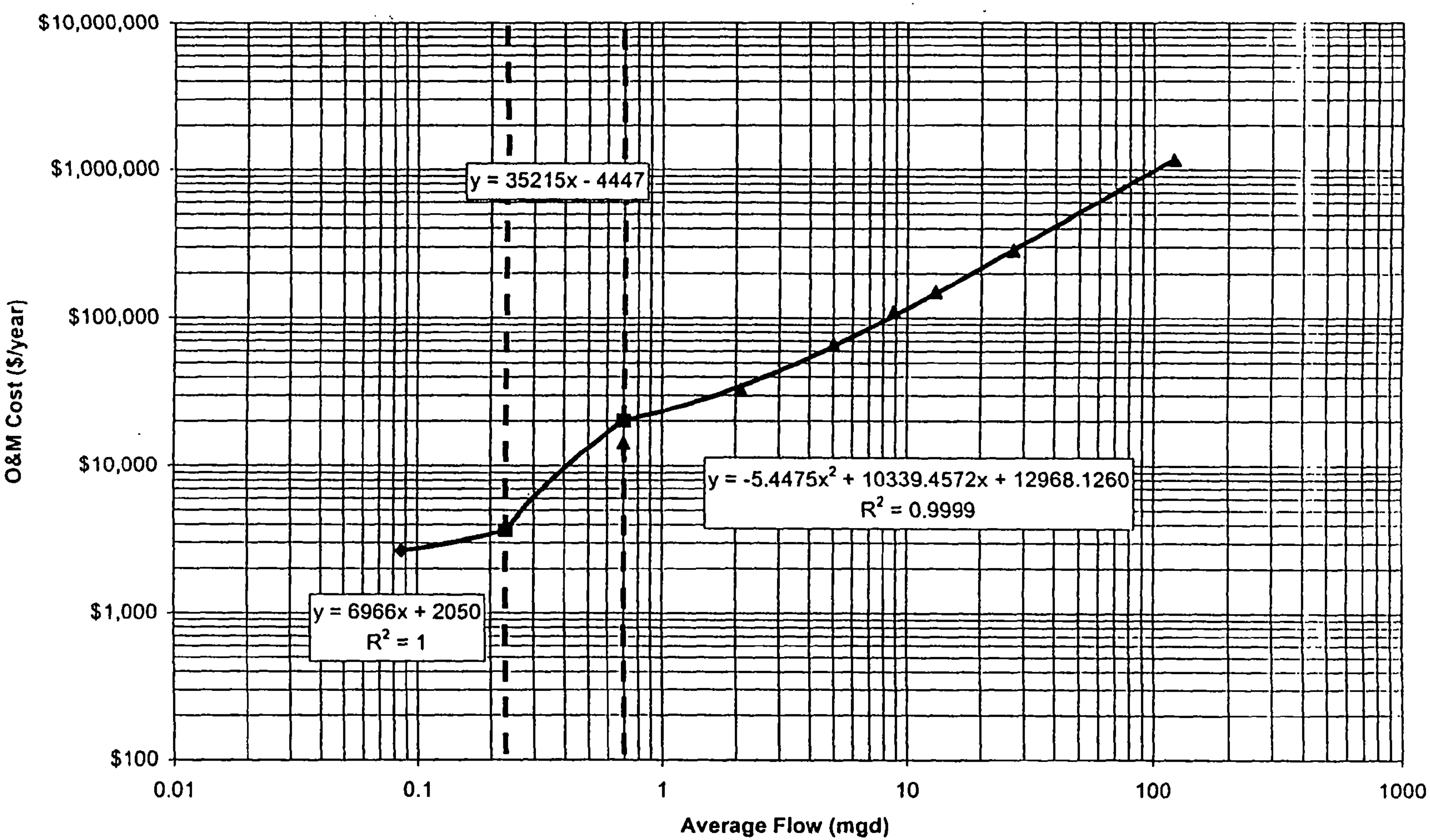


Figure 12-5
Non-Mechanical Dewatering and Dewatered Sludge Land Application
Coagulation Filtration
Disposal Capital Costs

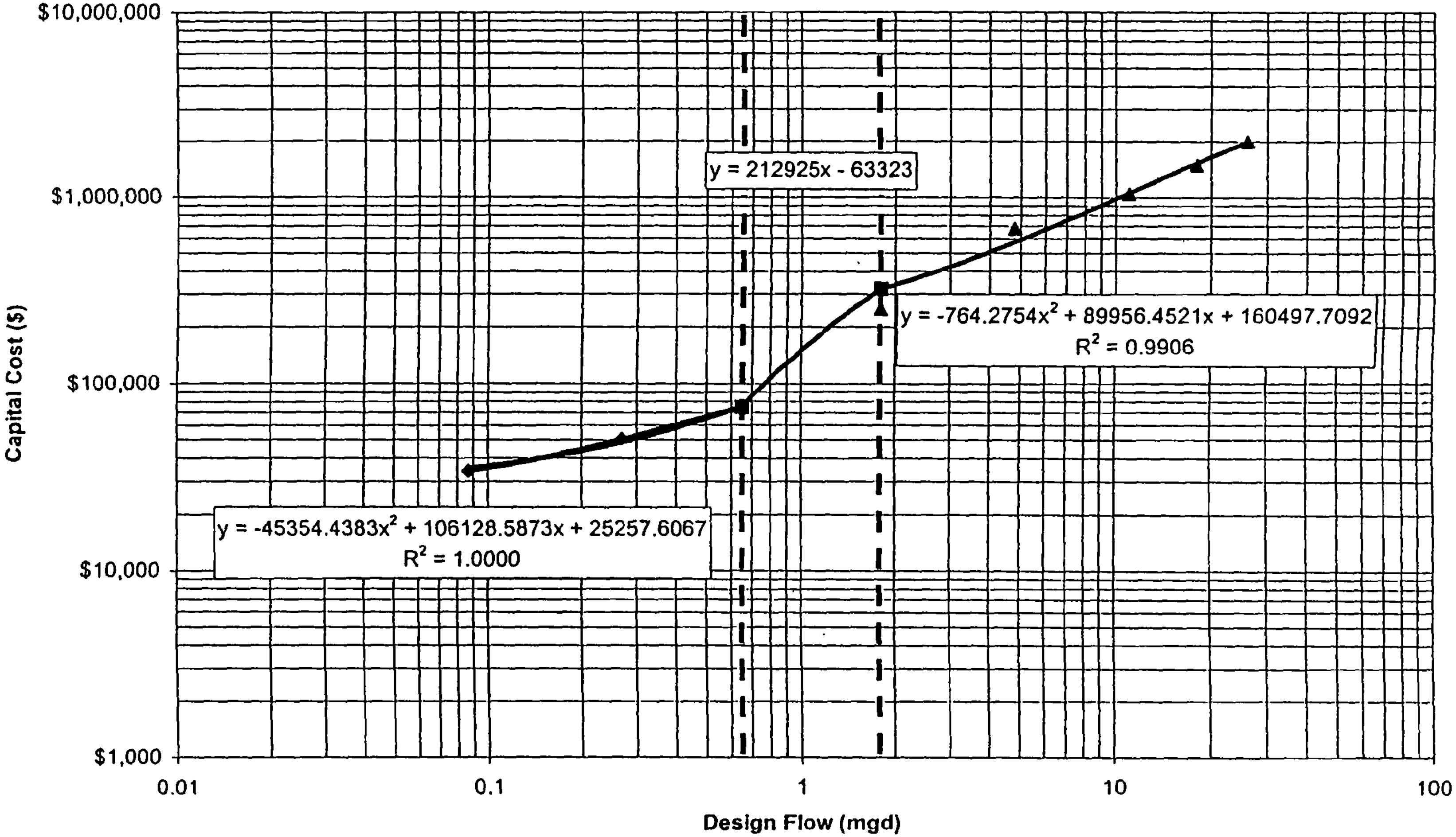


Figure 12-6
Non-Mechanical Dewatering and Dewatered Sludge Land Application
Coagulation Filtration
Disposal O&M Costs

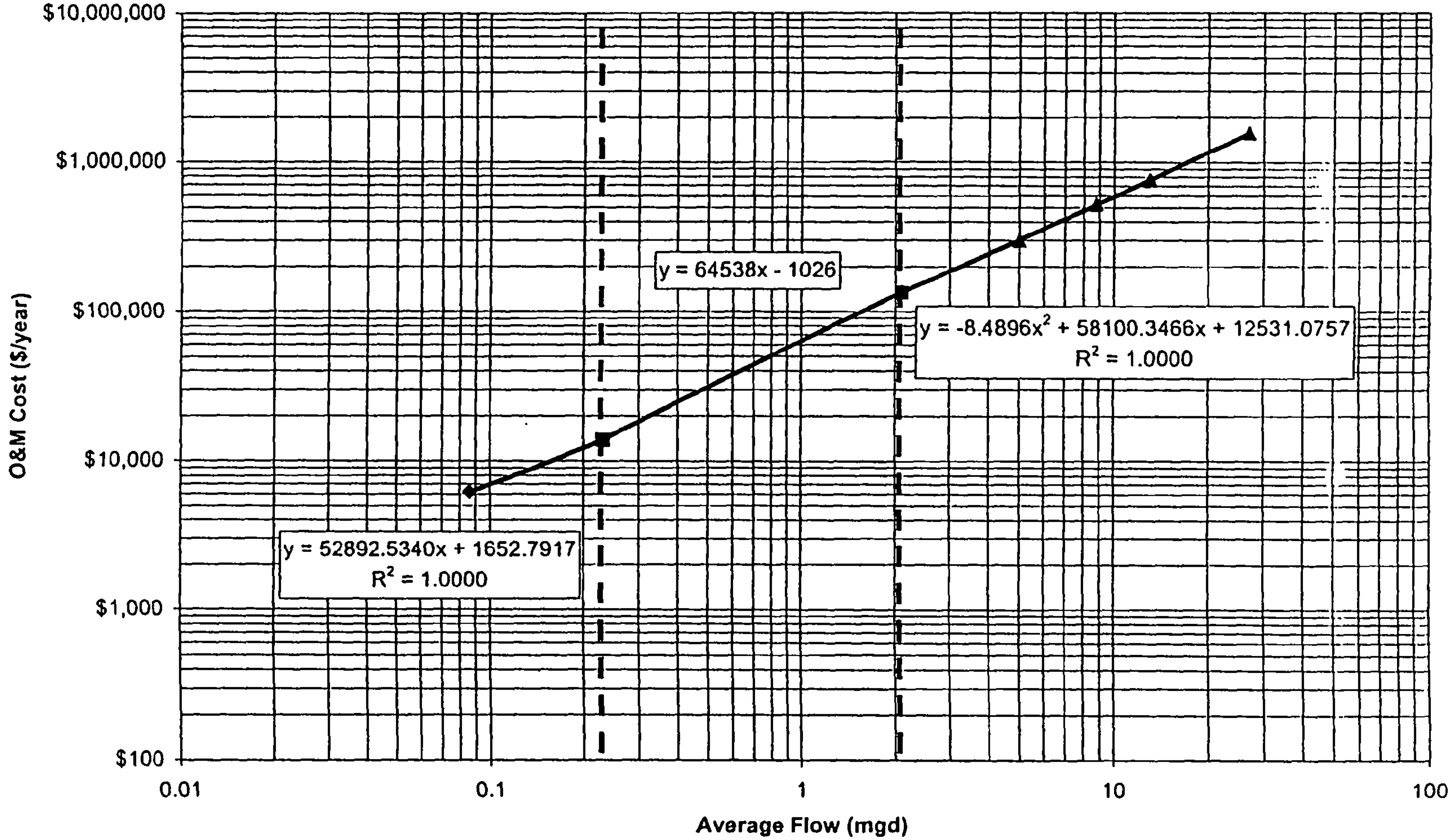
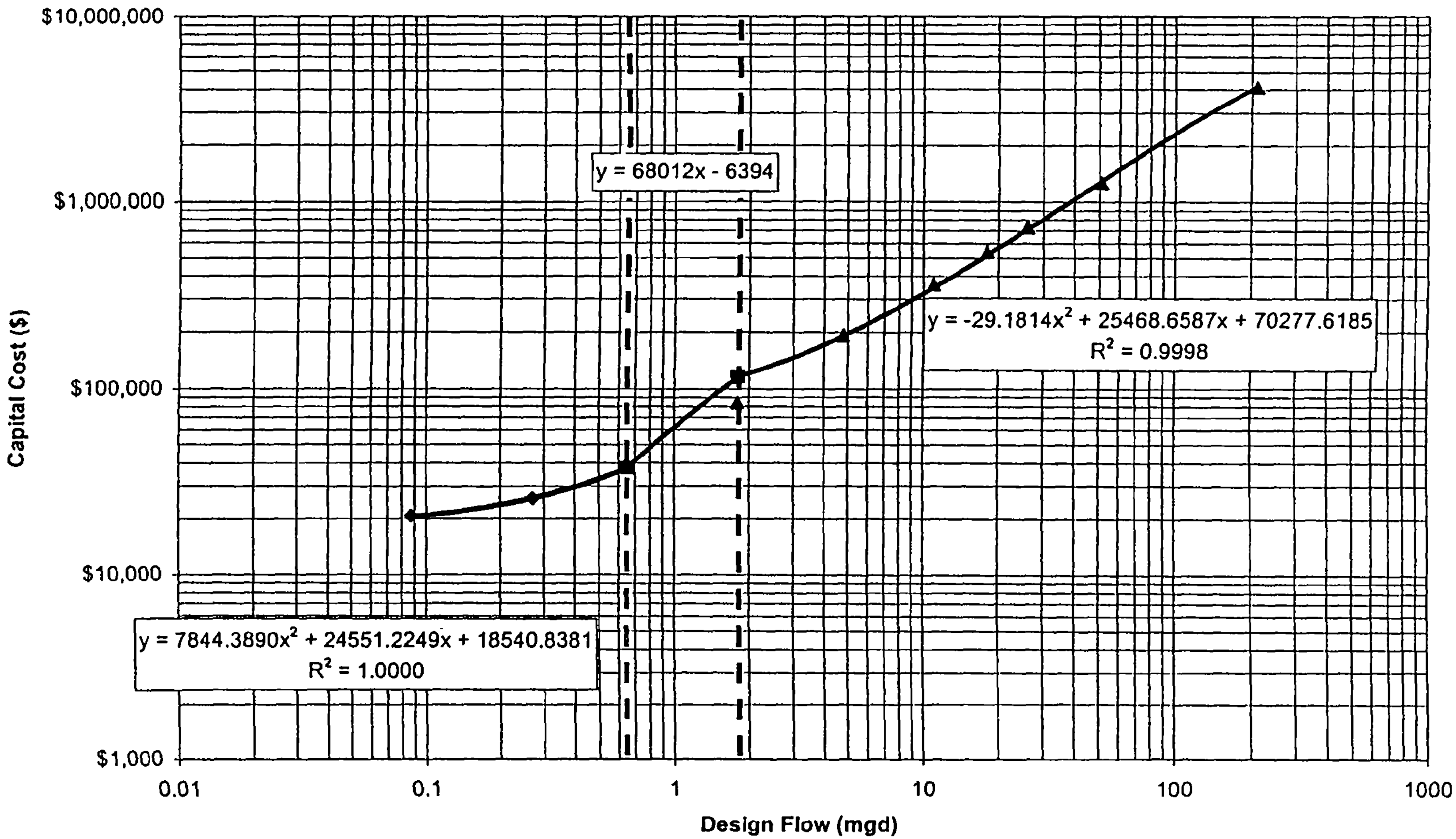


Figure 12-7
Liquid Sludge Application - Sprinkler System
Coagulation Filtration
Disposal Capital Costs



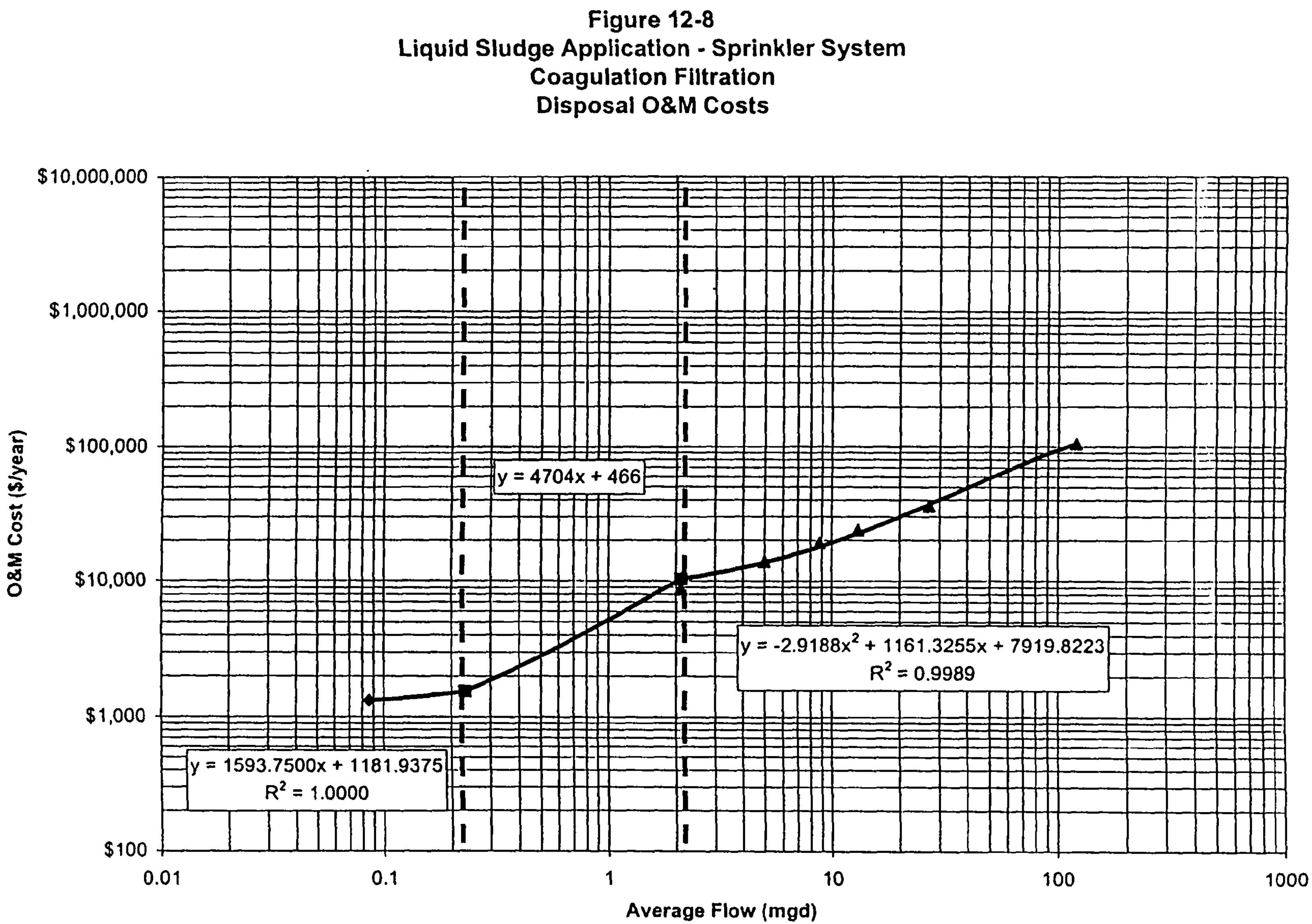


Figure 12-8
Liquid Sludge Application - Sprinkler System
Coagulation Filtration
Disposal O&M Costs
$10,000,000
$1,000,000
$100,000
$10,000
$1,000
$100
O&M Cost ($/year)
y = 4704x + 466
y = -2.9188x2 + 1161.3255x + 7919.8223
R2 = 0.9989
y = 1593.7500x + 1181.9375
R2 = 1.0000
0.01
0.1
1
10
100
1000
Average Flow (mgd)

Figure 12-9
Liquid Sludge Application - Trucking System
Coagulation Filtration
Disposal Capital Costs

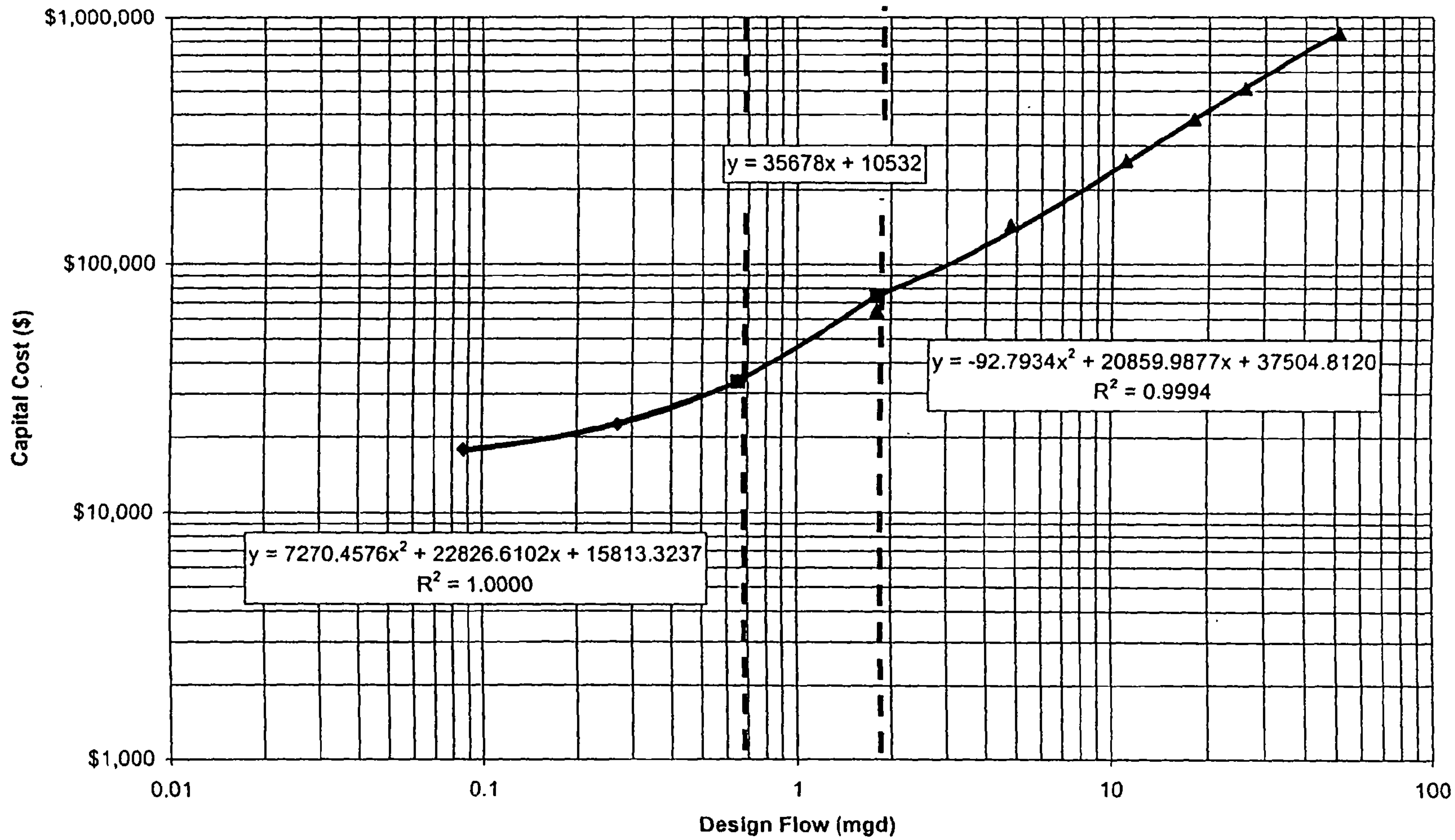


Figure 12-10
Liquid Sludge Application - Trucking System
Coagulation Filtration
Disposal O&M Costs

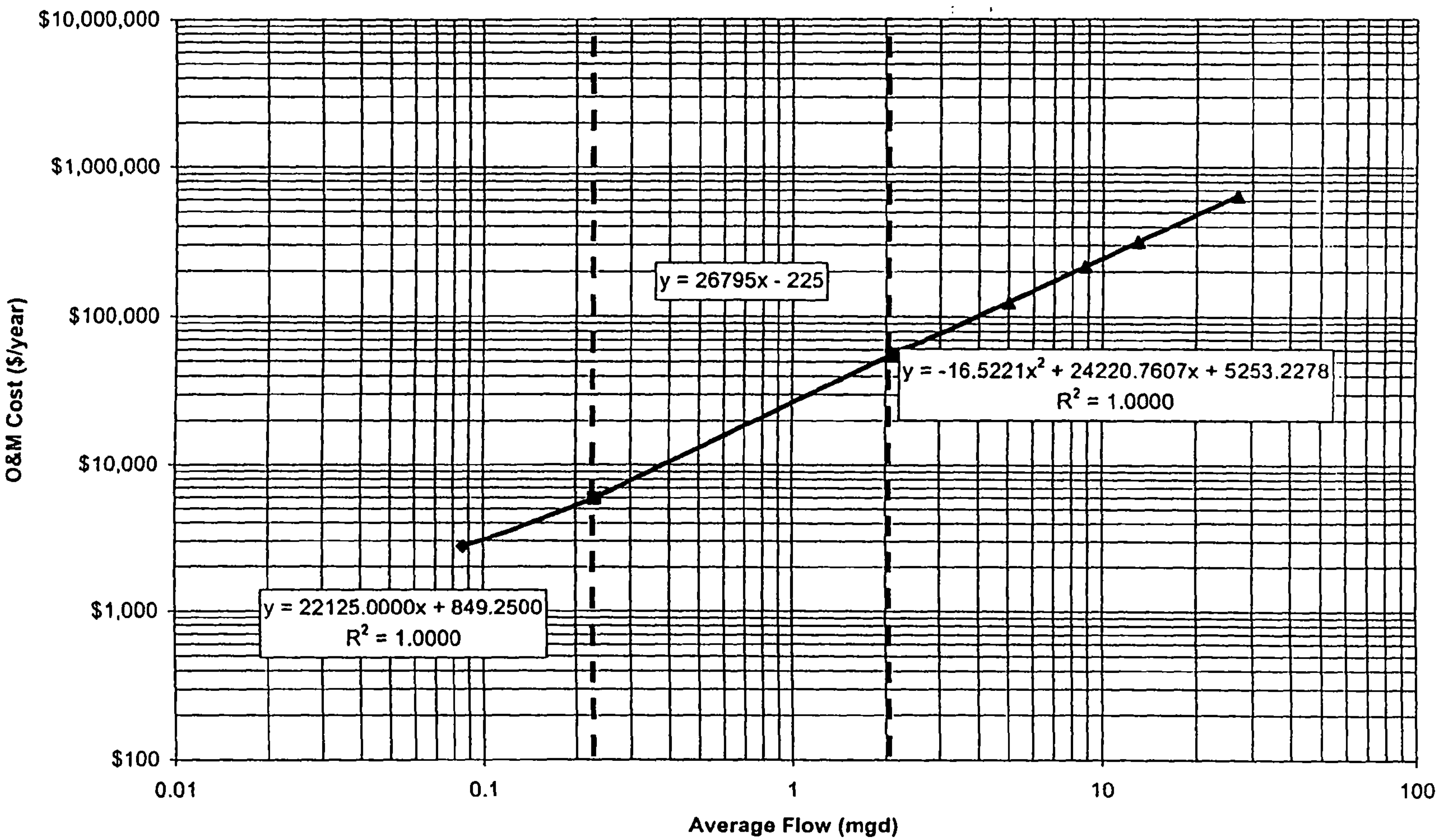


Figure 12-11
Mechanical Dewatering and Non-Hazardous Landfill
Lime Softening
Disposal Capital Costs

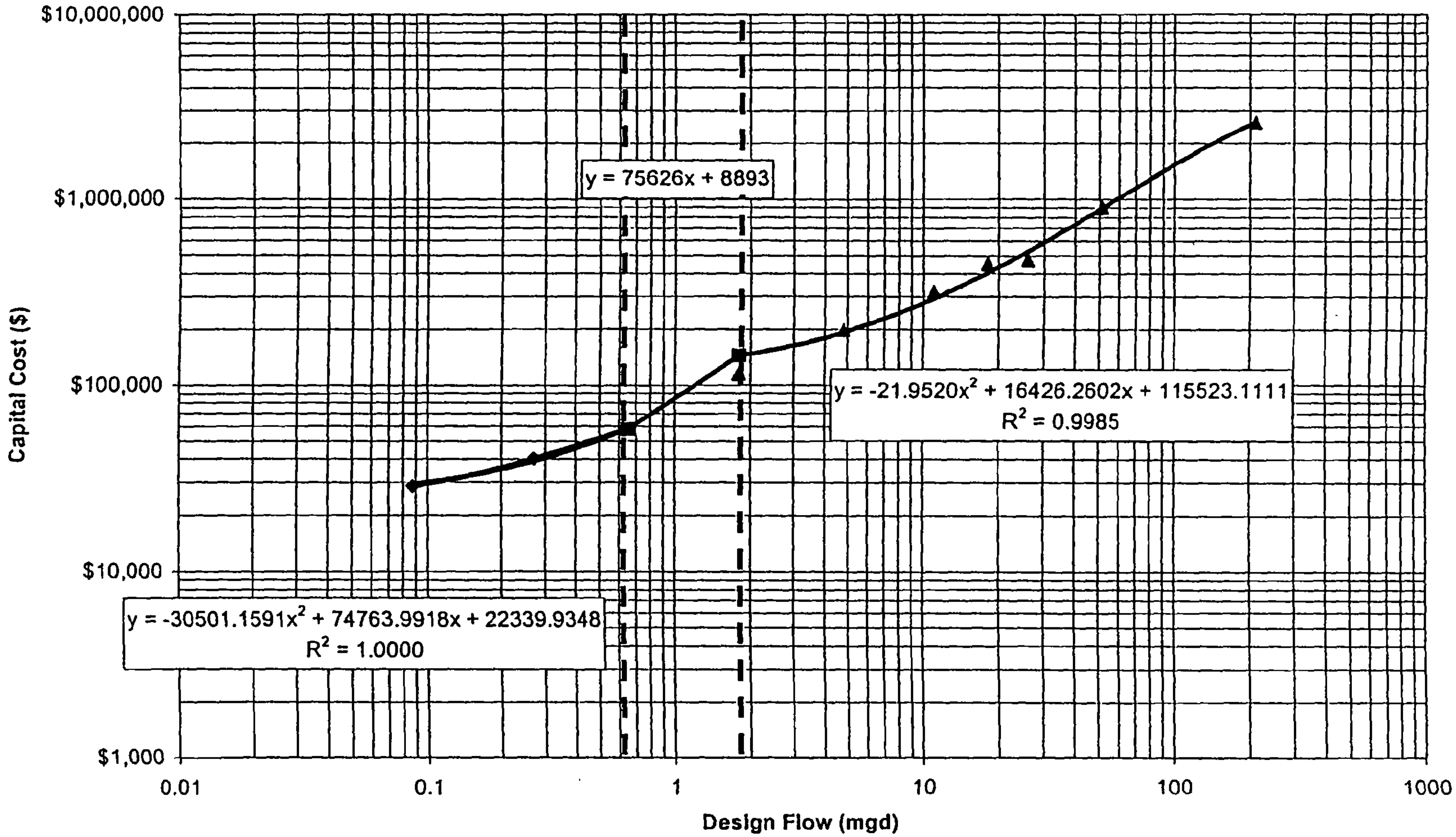


Figure 12-12
Mechanical Dewatering and Non-Hazardous Landfill
Lime Softening
Disposal O&M Costs

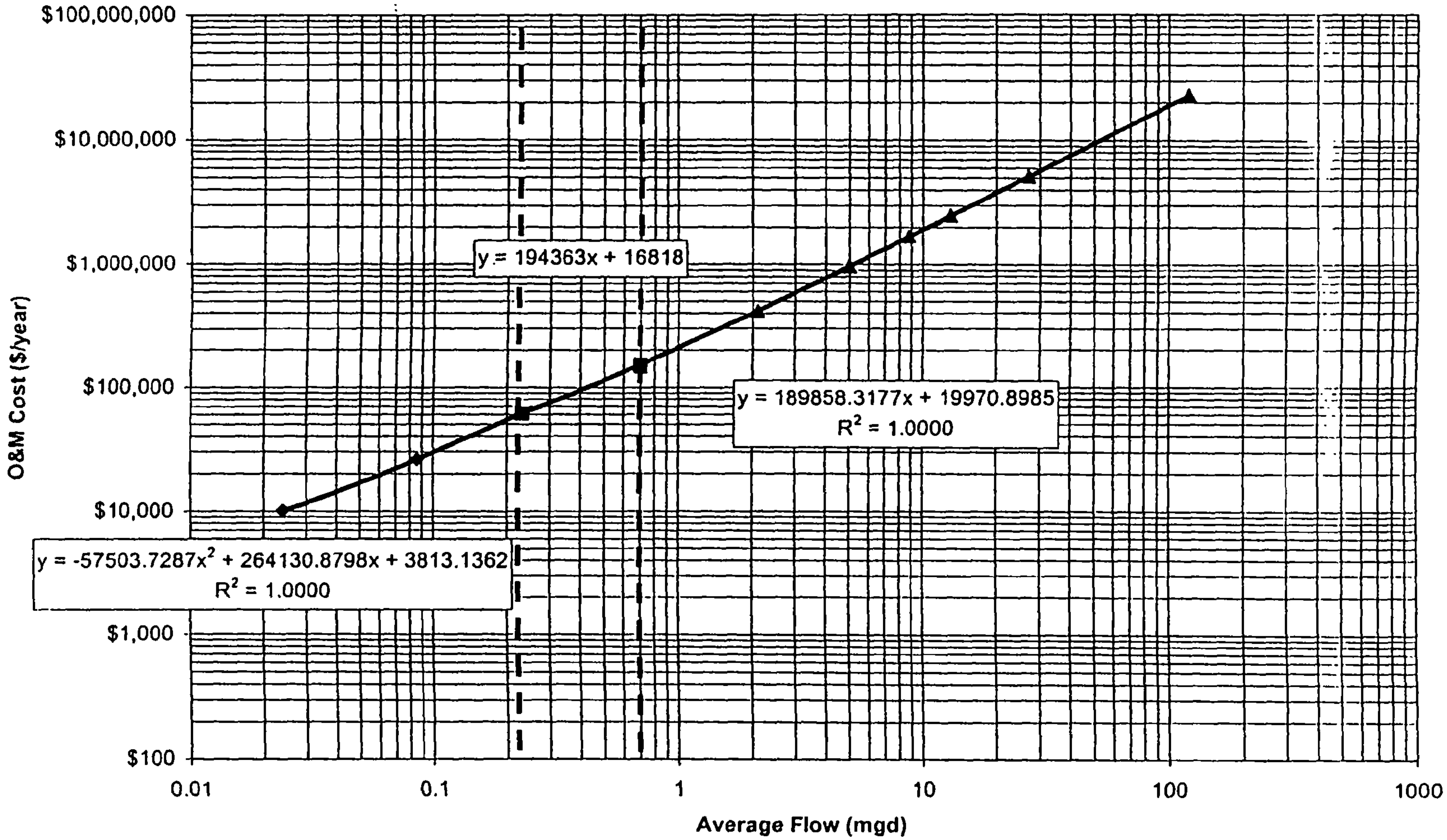


Figure 12-13
Non-Mechanical Dewatering and Non-Hazardous Landfill
Lime Softening
Disposal Capital Costs

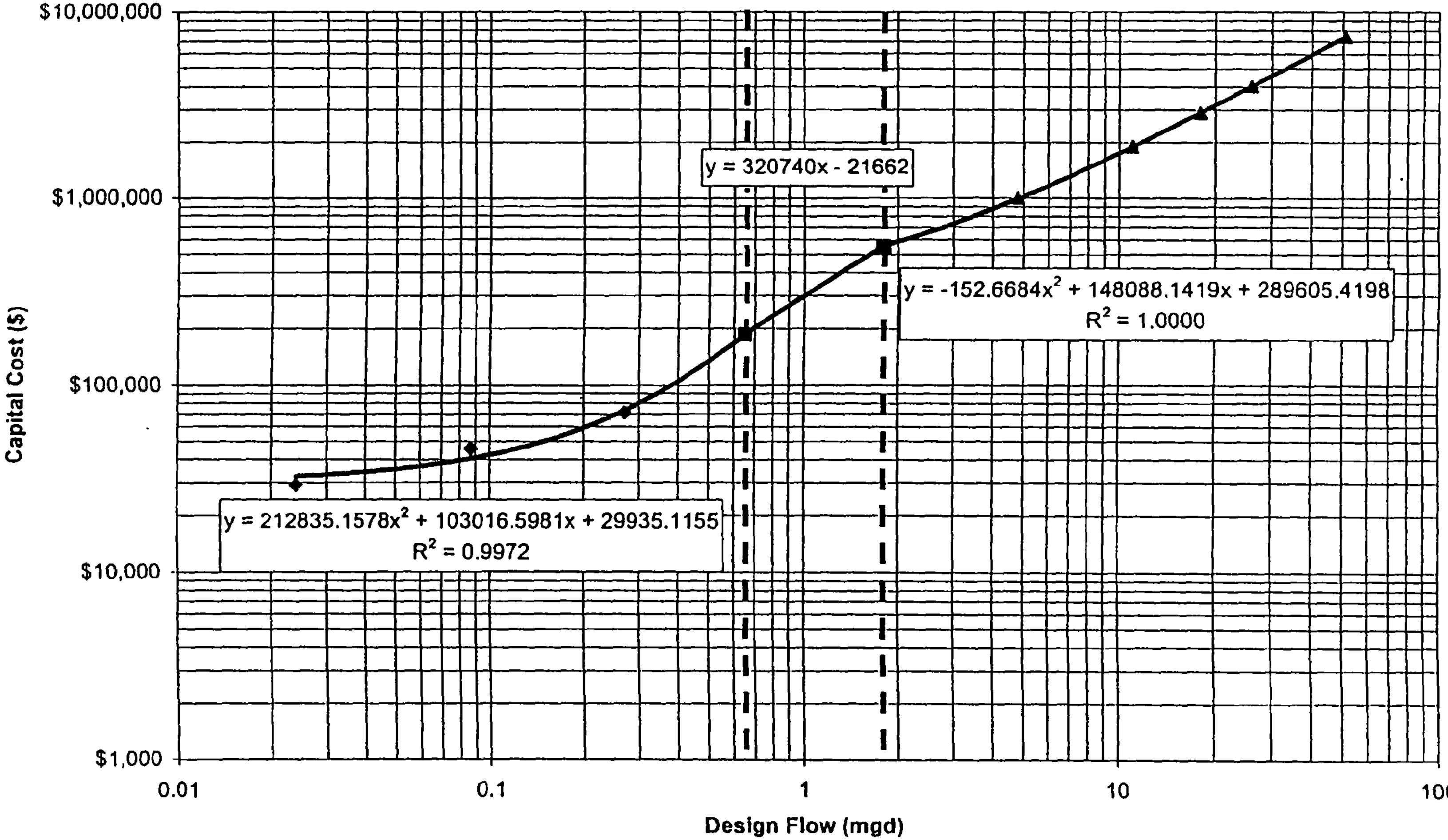


Figure 12-14
Non-Mechanical Dewatering and Non-Hazardous Landfill
Lime Softening
Disposal O&M Costs

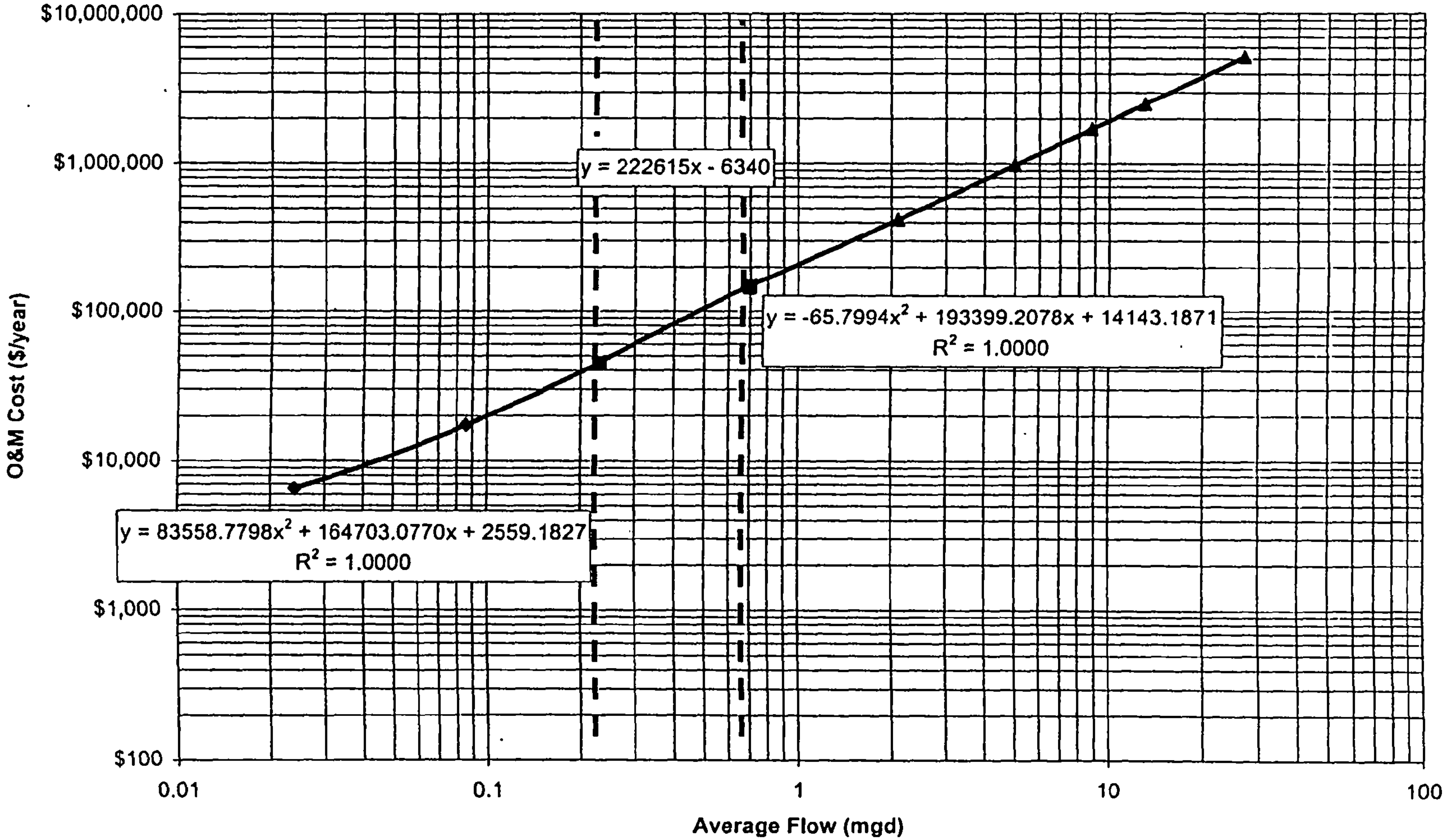


Figure 12-15
Non-Mechanical Dewatering and Dewatered Sludge Land Application
Lime Softening
Disposal Capital Costs

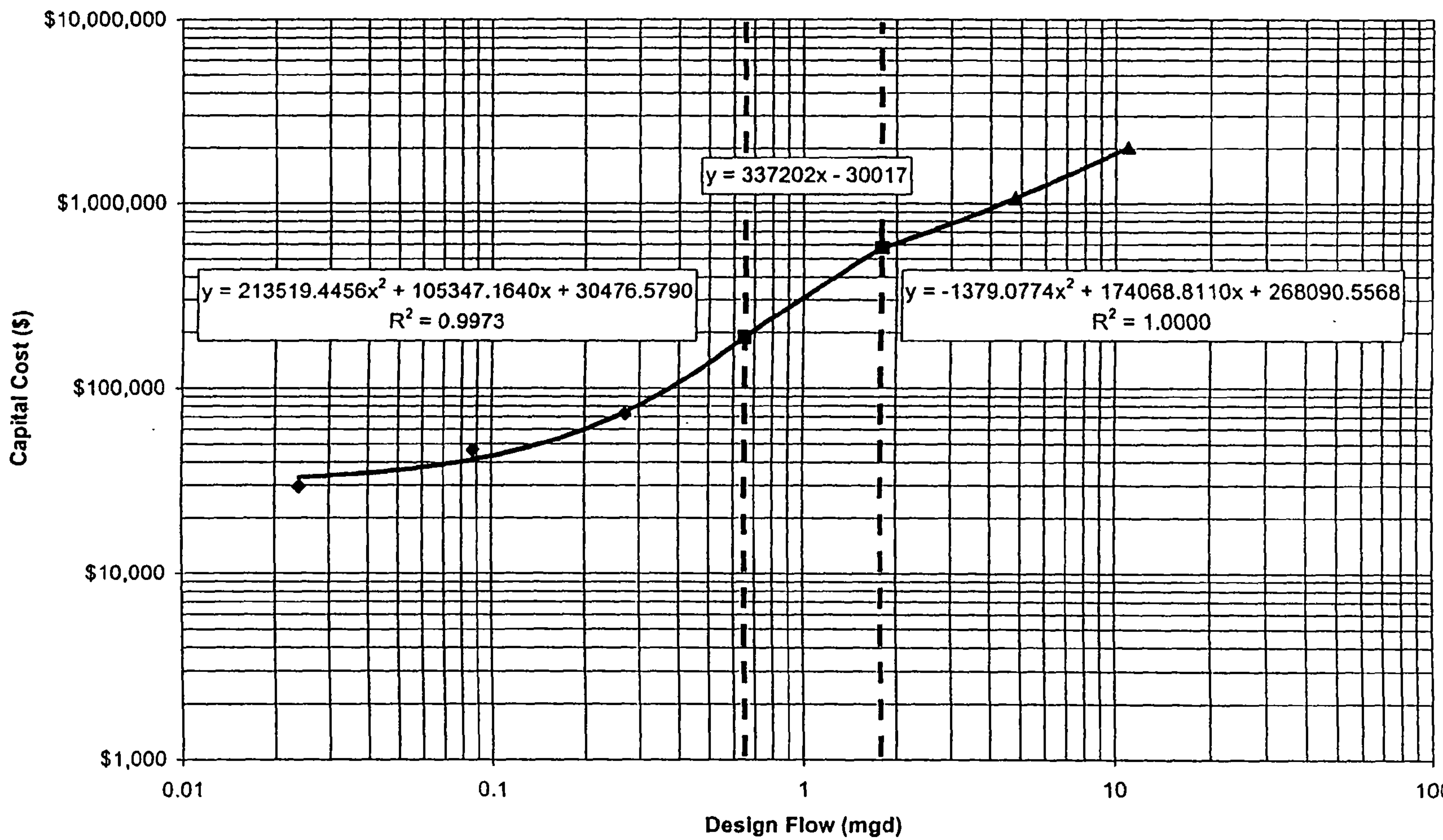


Figure 12-16
Non-Mechanical Dewatering and Dewatered Sludge Land Application
Lime Softening
Disposal O&M Costs

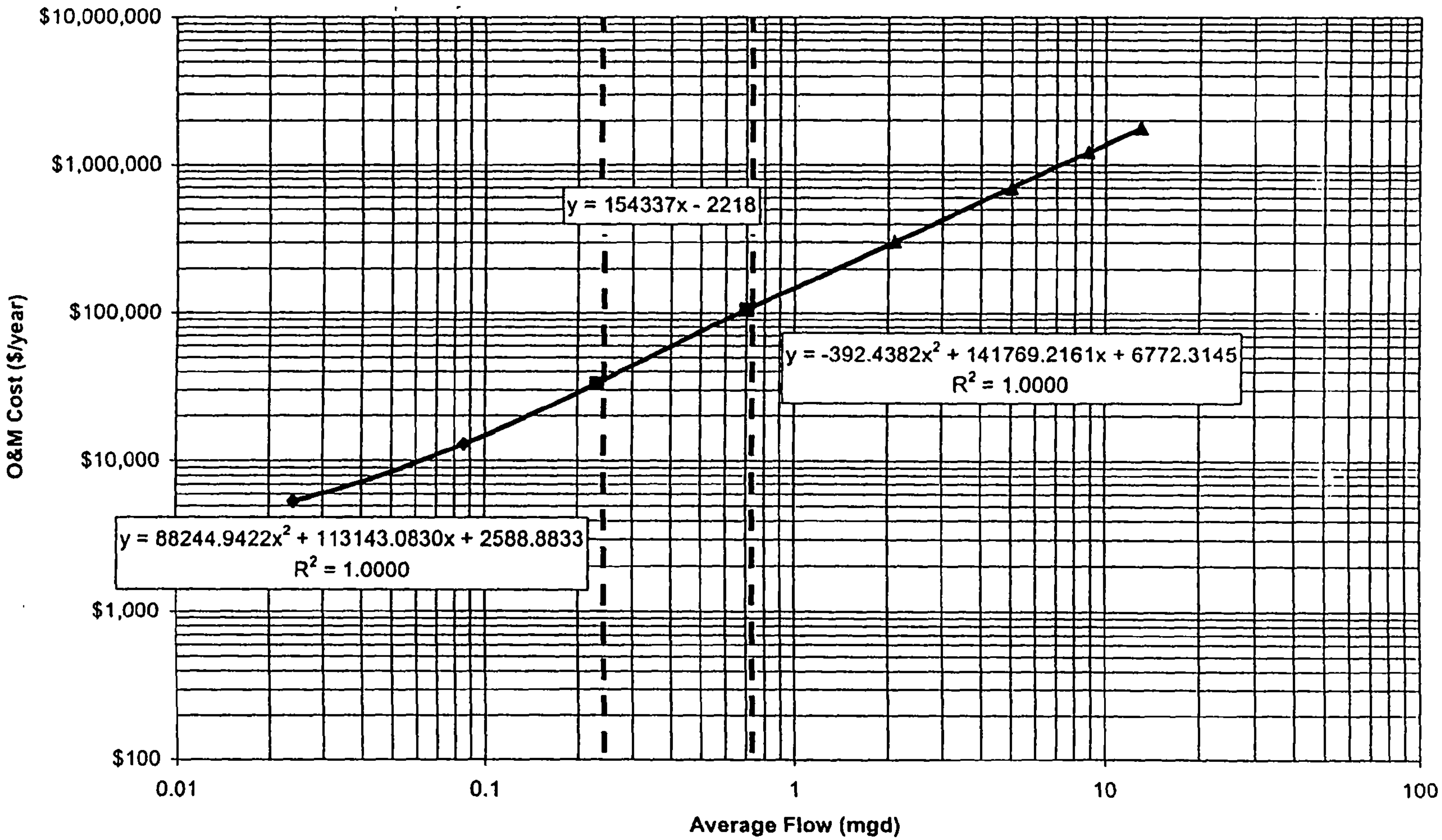


Figure 12-17
Liquid Sludge Application - Sprinkler System
Lime Softening
Disposal Capital Costs

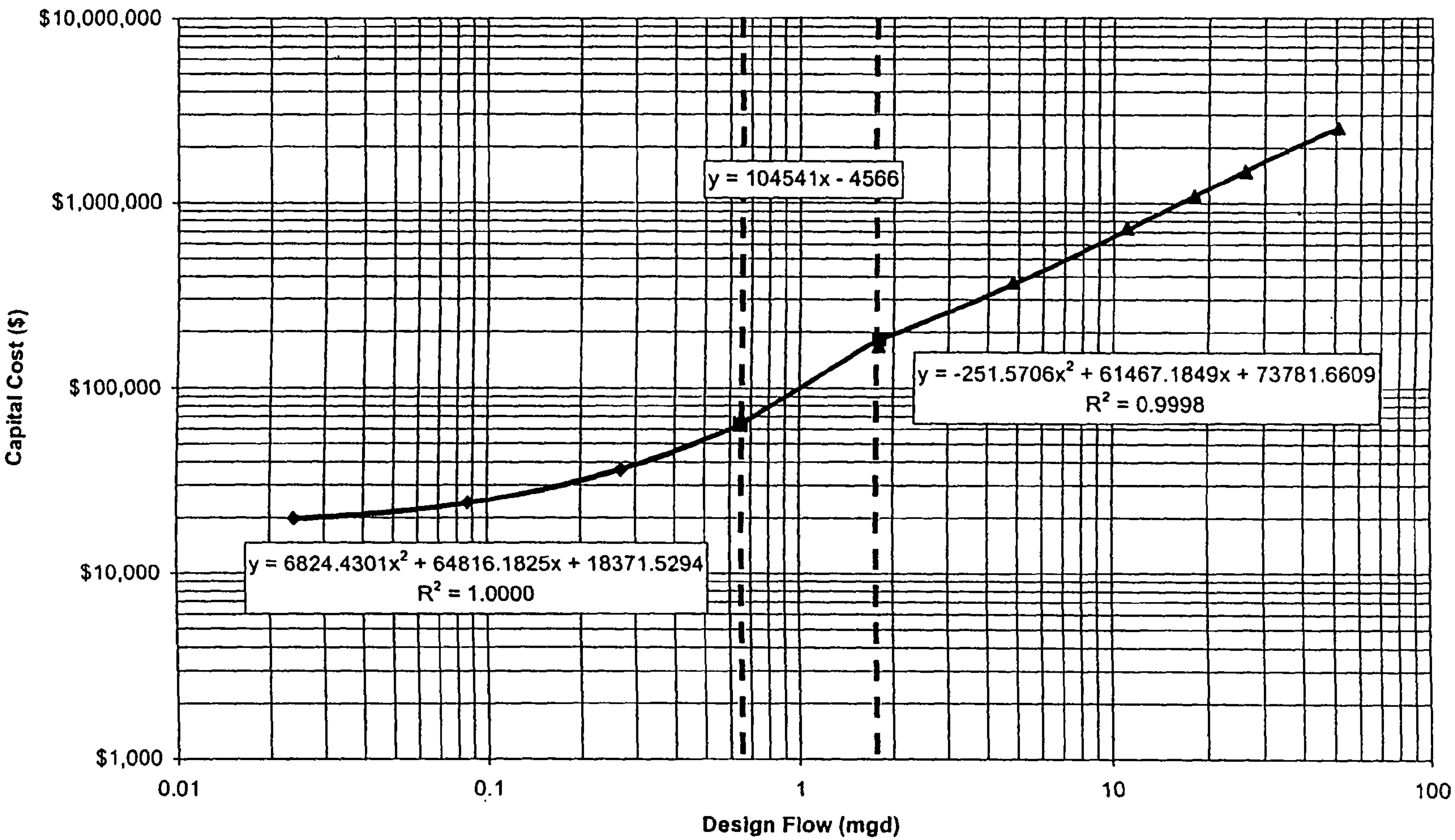


Figure 12-18
Liquid Sludge Application - Sprinkler System
Lime Softening
Disposal O&M Costs

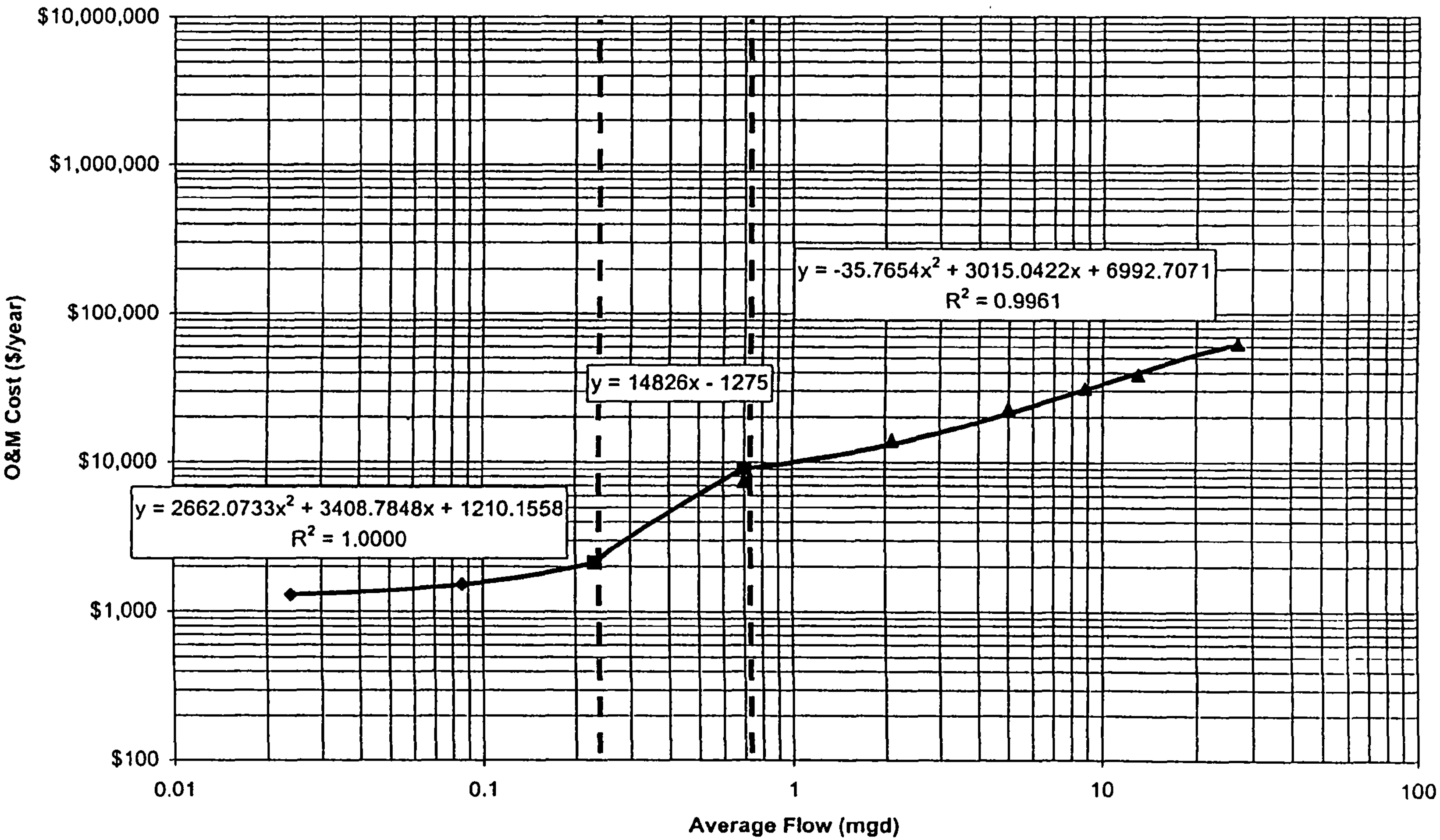


Figure 12-19
Liquid Sludge Application - Trucking System
Lime Softening
Disposal Capital Costs

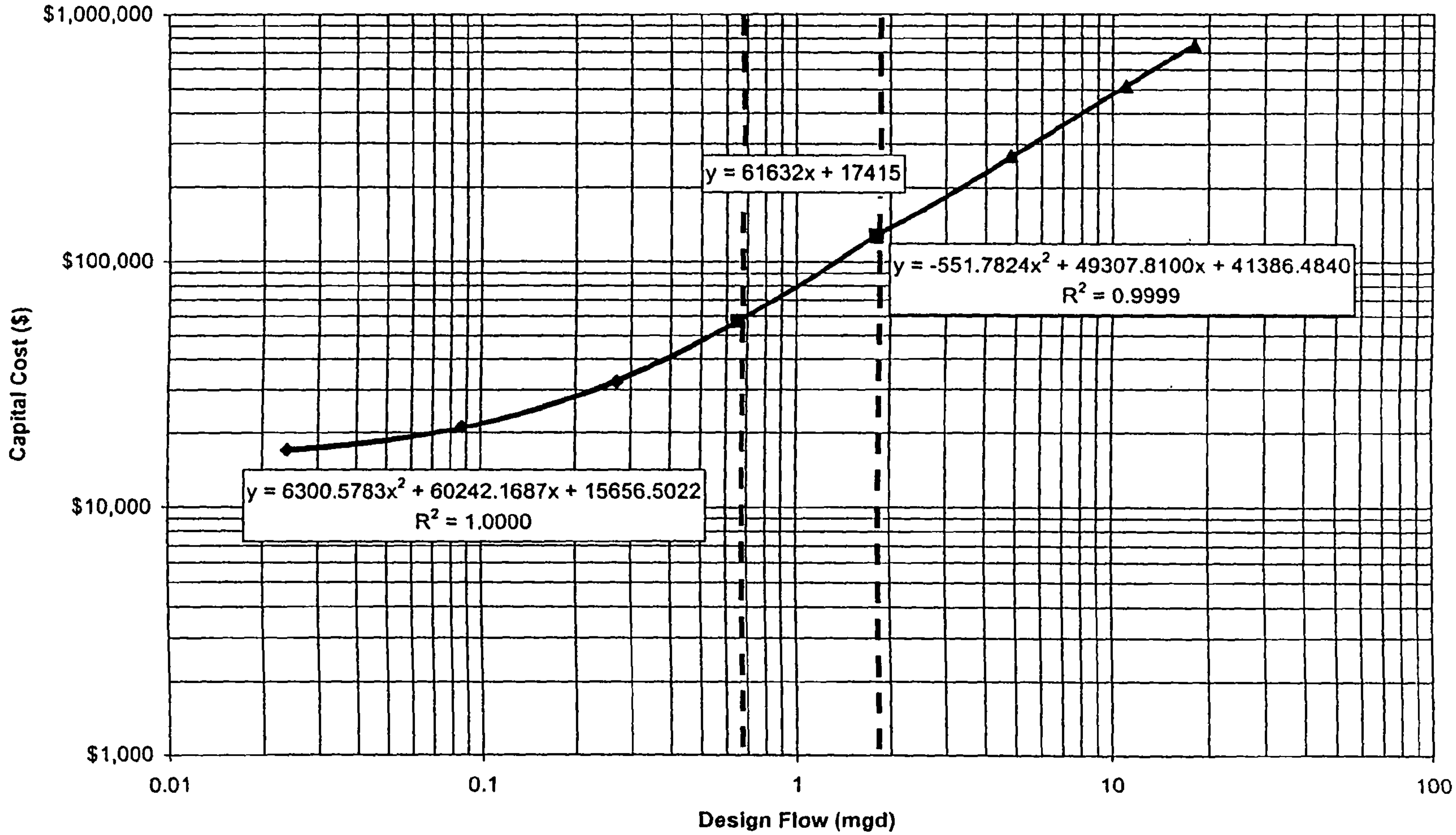


Figure 12-20
Liquid Sludge Application - Trucking System
Lime Softening
Disposal O&M Costs

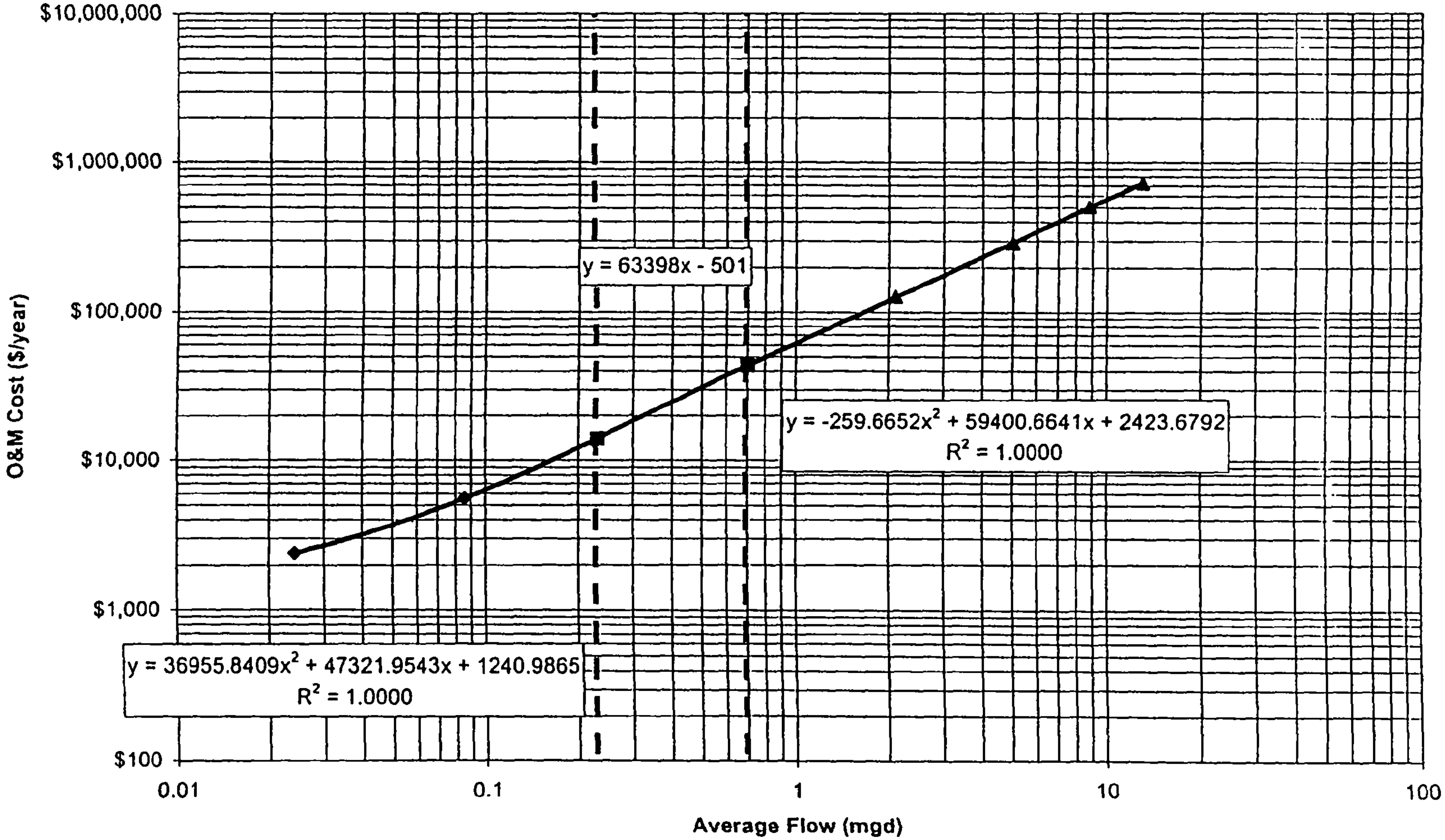


Figure 12-21
Chemical Precipitation
Ion Exchange
Disposal Capital Costs

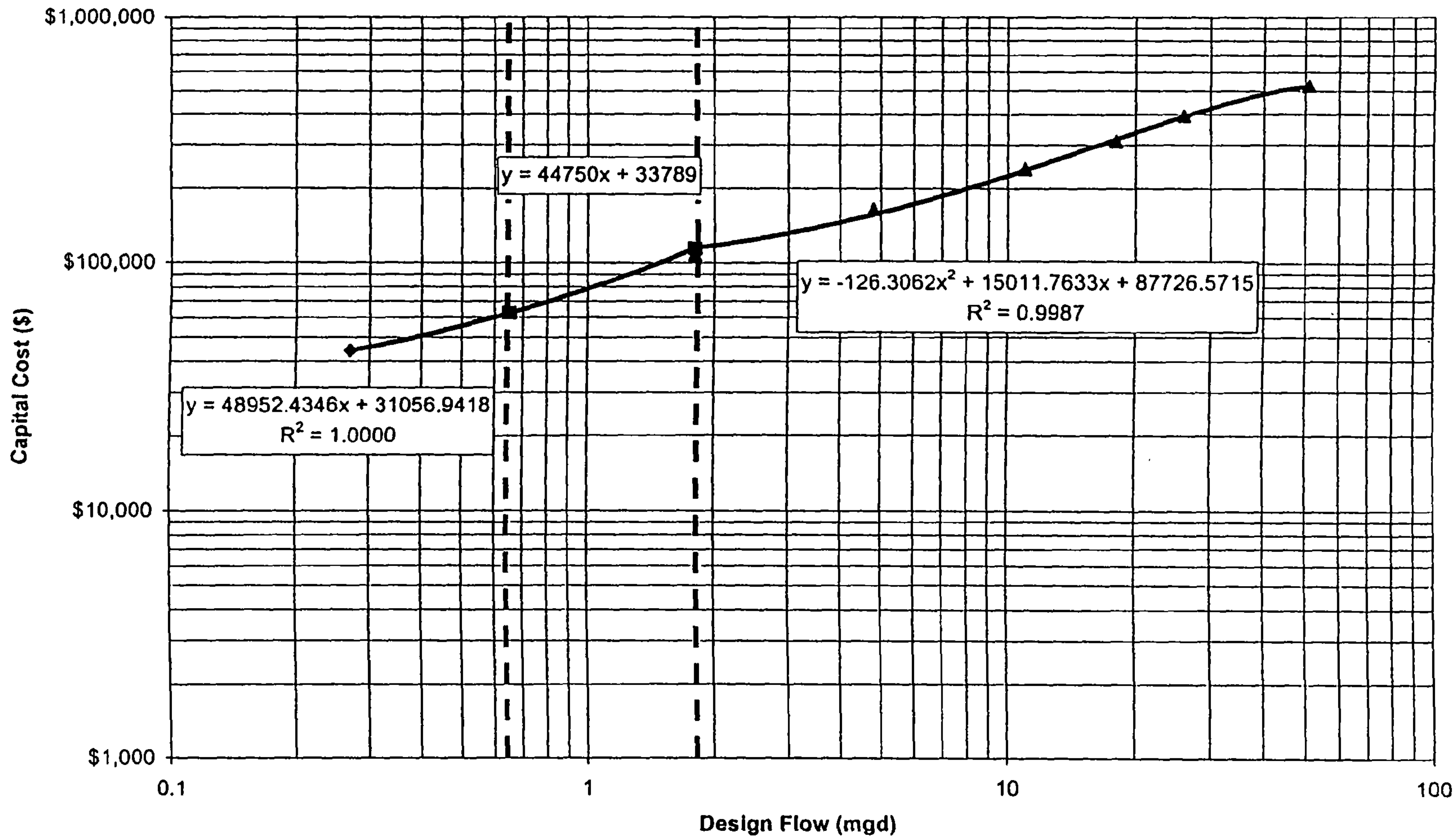


Figure 12-22
Chemical Precipitation
Ion Exchange
Disposal O&M Costs

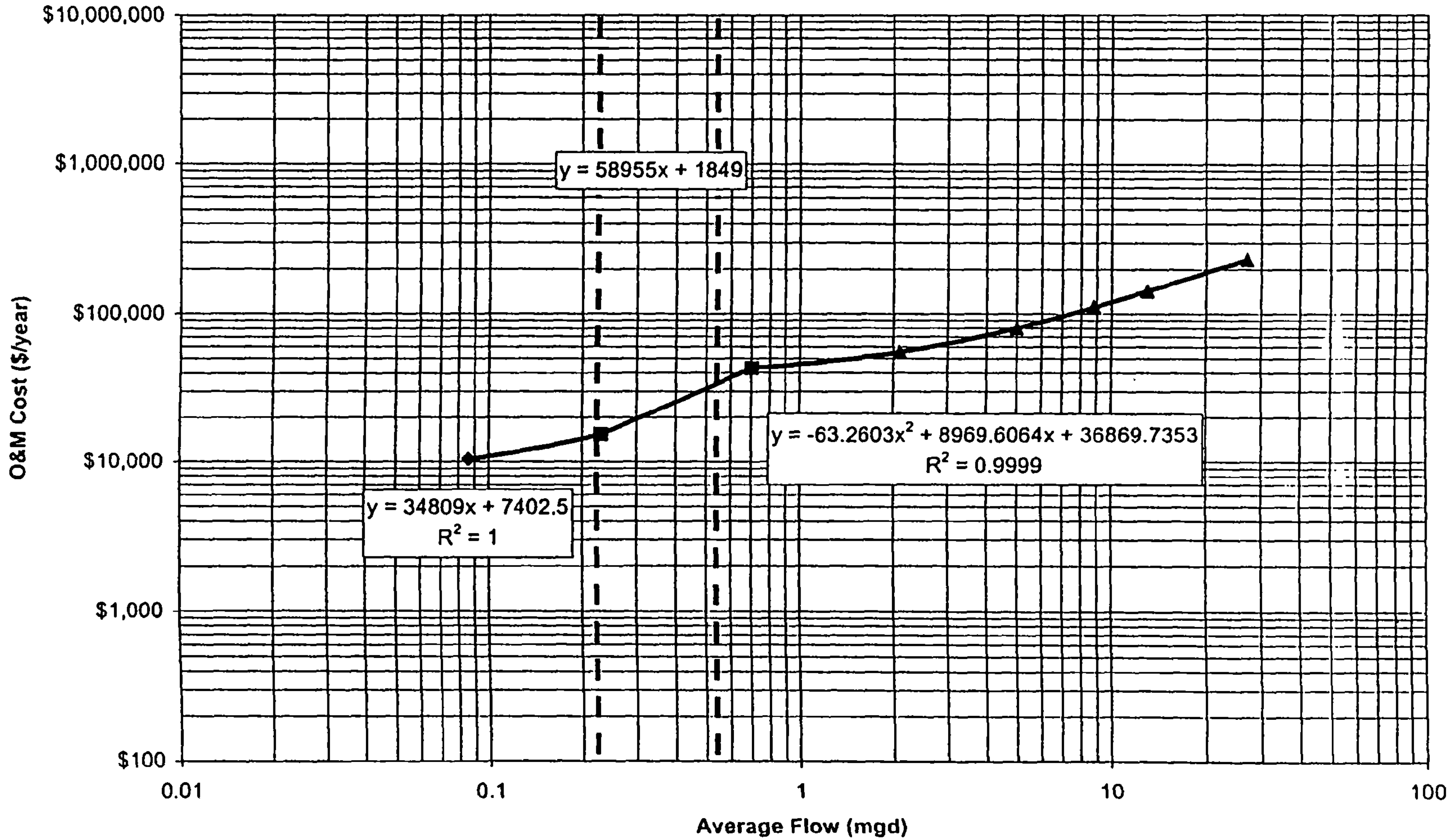


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Figure 12-23
Direct Discharge - 500' of Pipe
Ion Exchange
Disposal Capital Costs

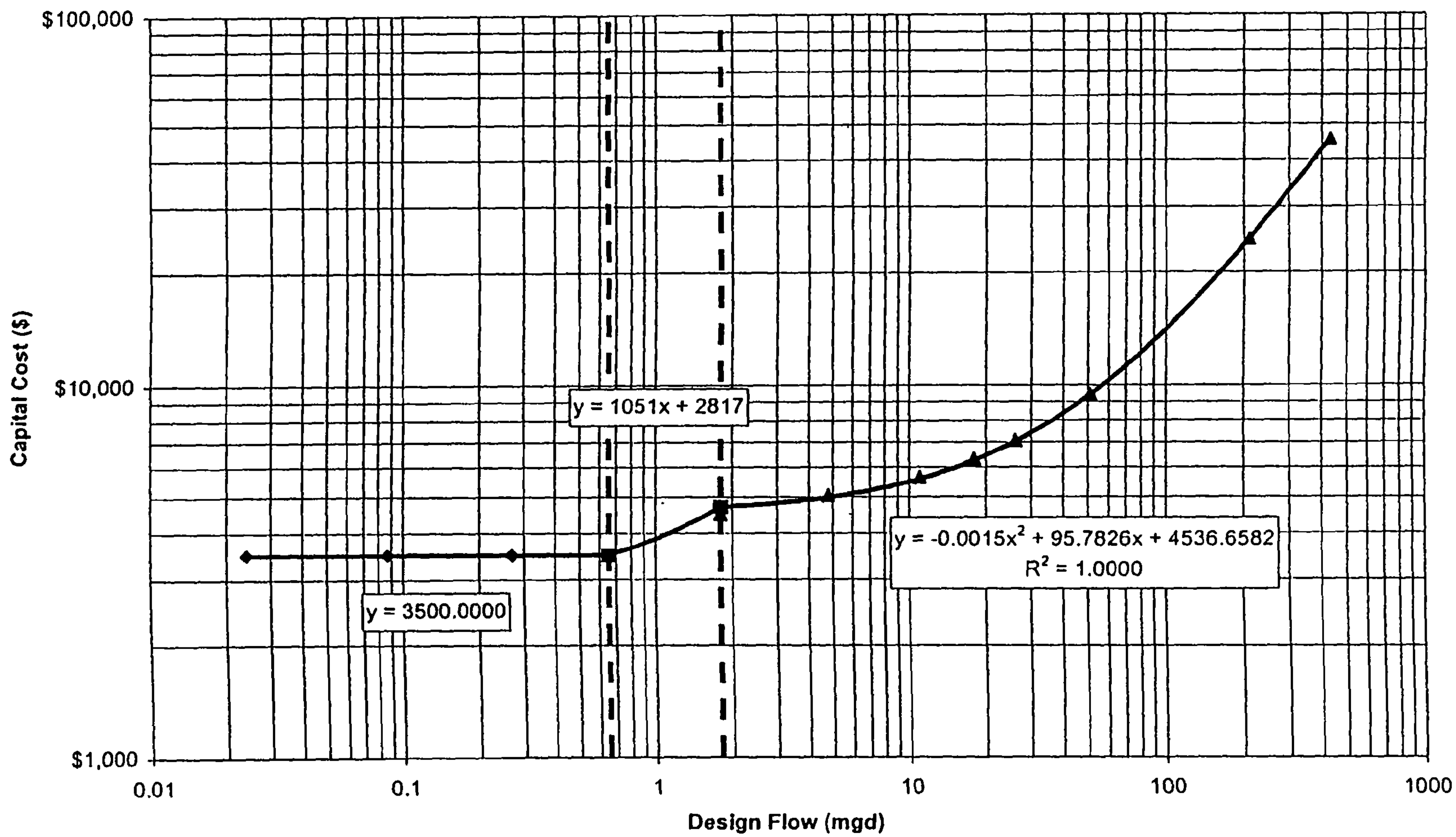


Figure 12-24
Direct Discharge - 500' of Pipe
Ion Exchange
Disposal O&M Costs

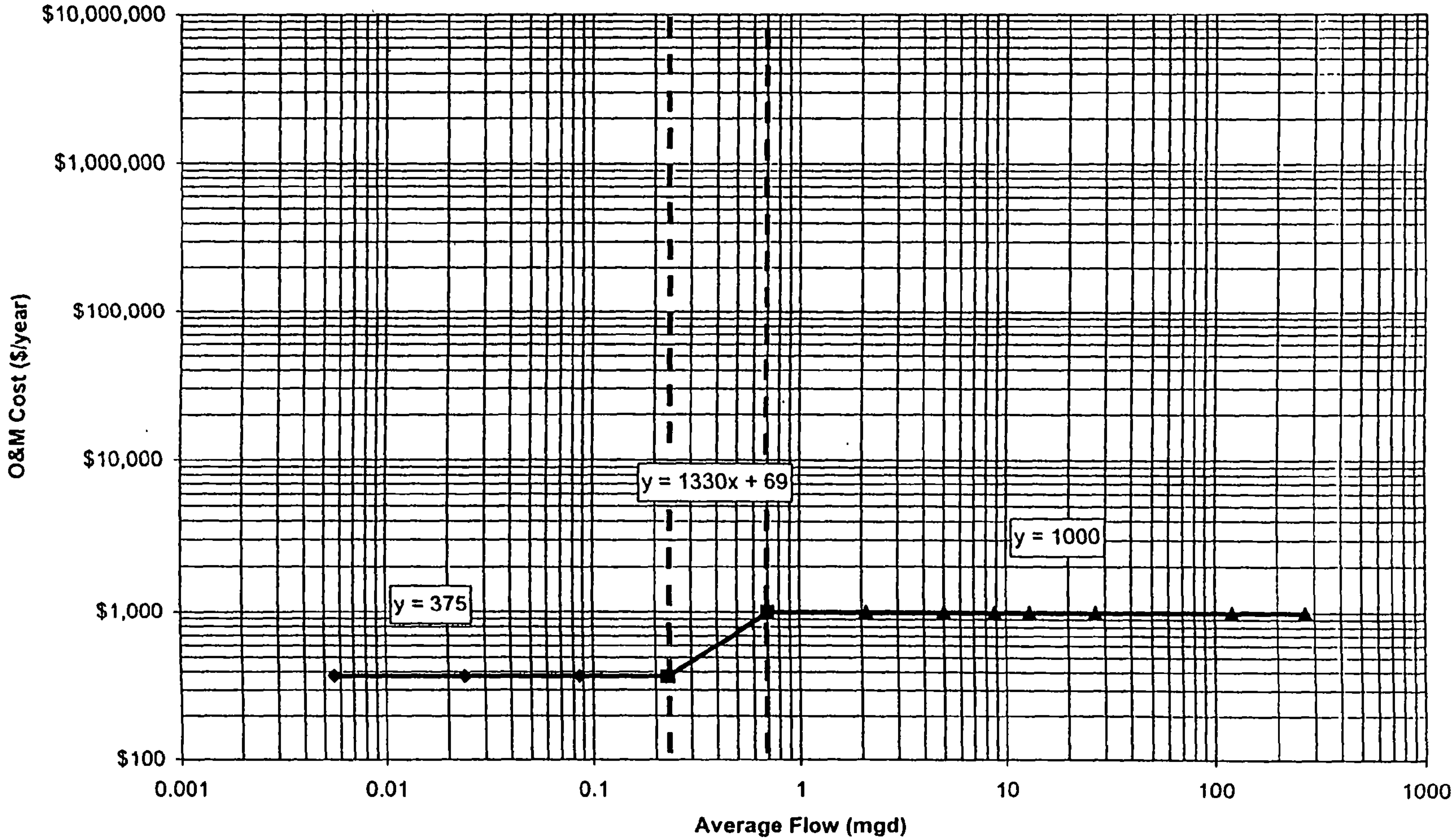


Figure 12-25
Direct Discharge - 1000' of Pipe
Ion Exchange
Disposal Capital Costs

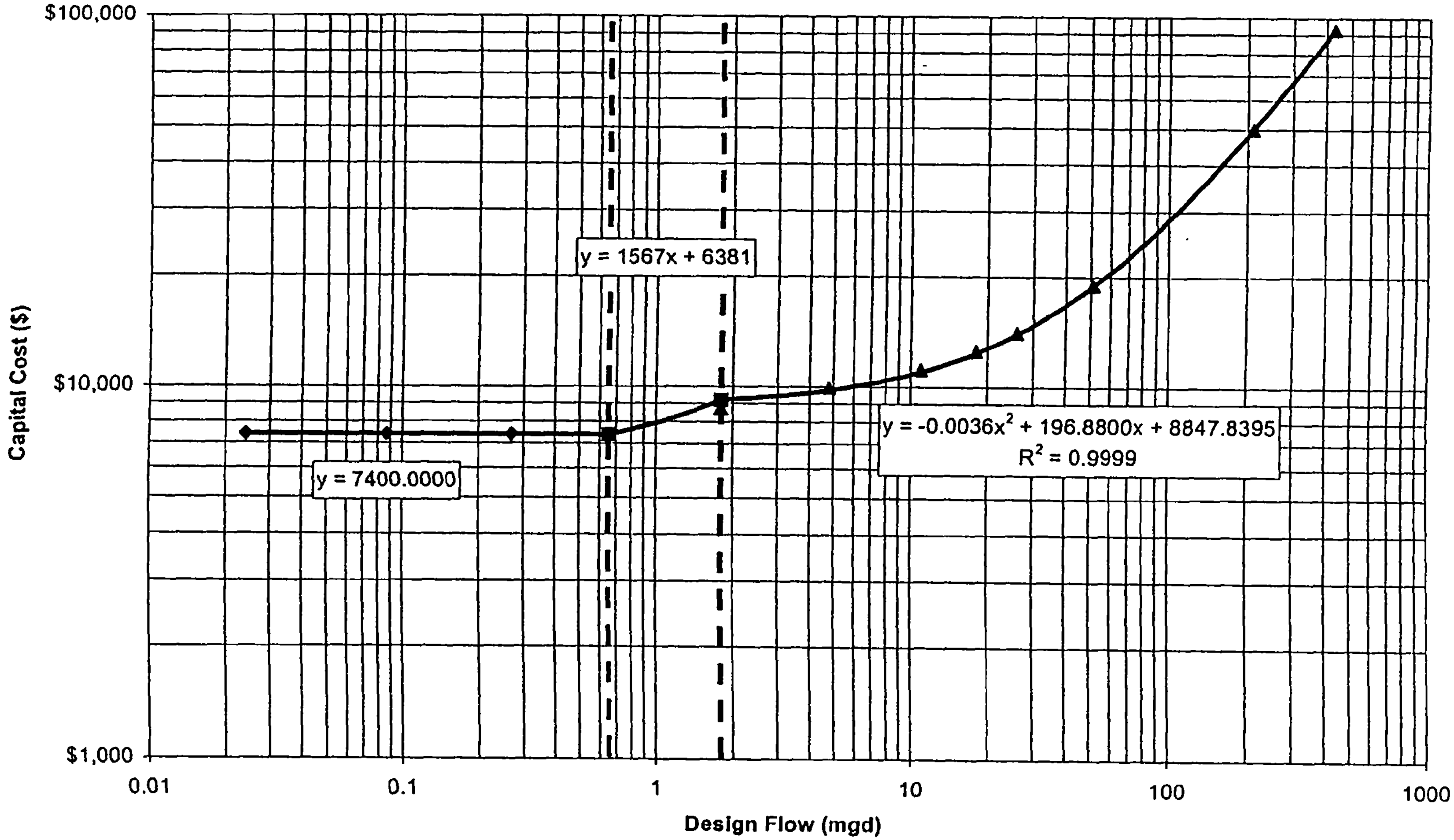


Figure 12-26
Direct Discharge - 1000' of Pipe
Ion Exchange
Disposal O&M Costs

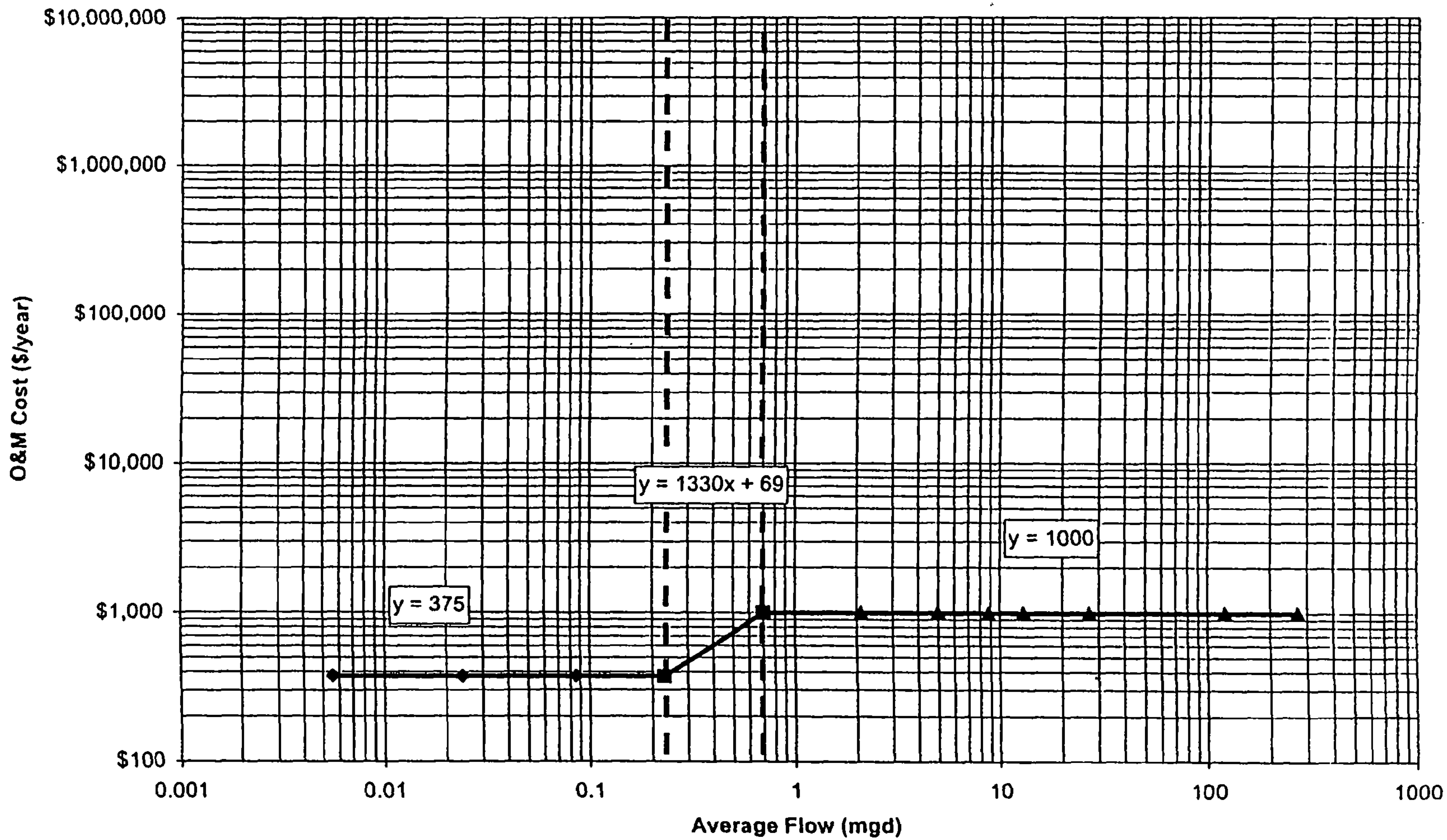


Figure 12-27
Evaporation Pond and Non-Hazardous Landfill
Ion Exchange
Disposal Capital Costs

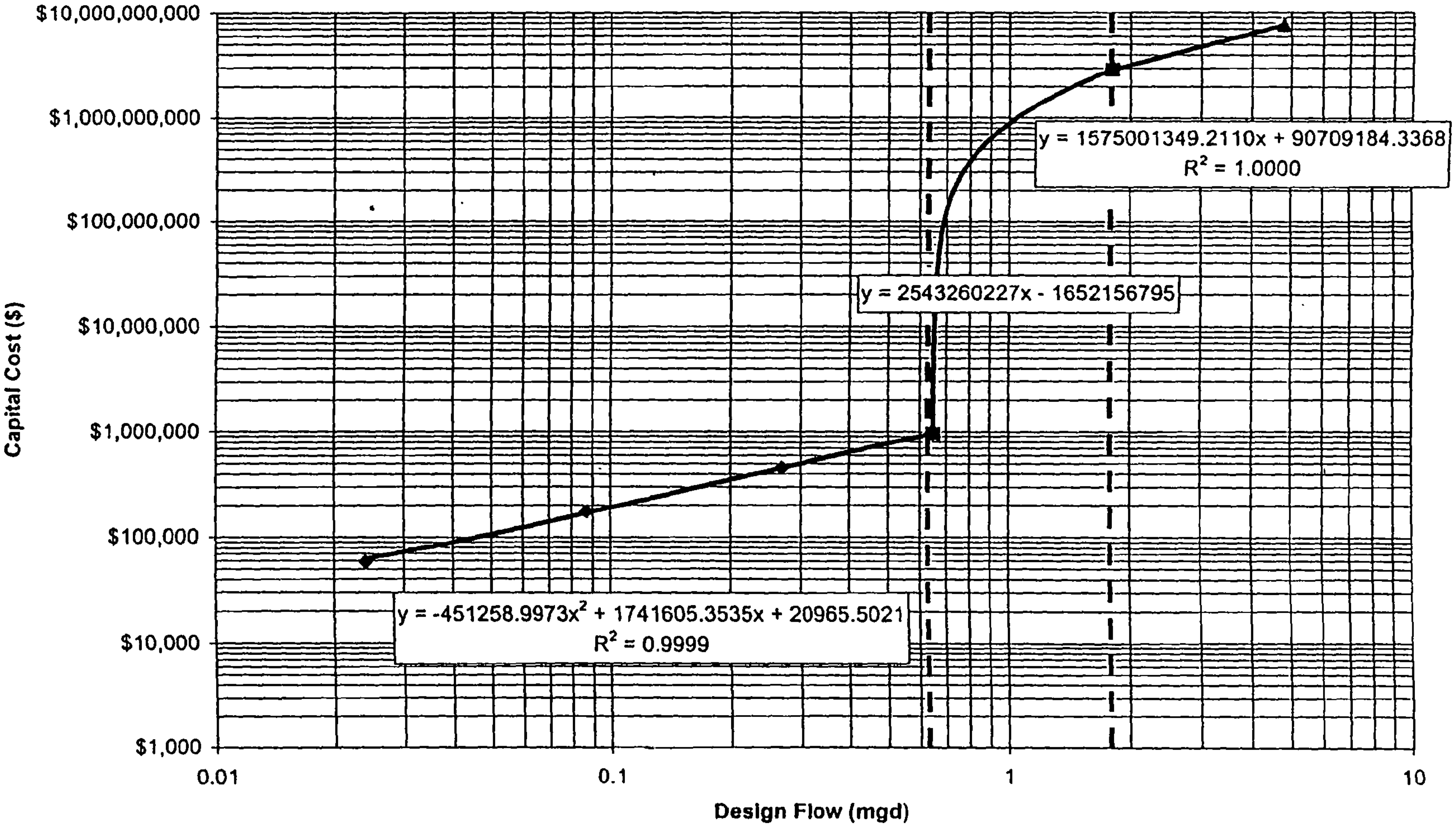


Figure 12-28
Evaporation Pond and Non-Hazardous Landfill
Ion Exchange
Disposal O&M Costs

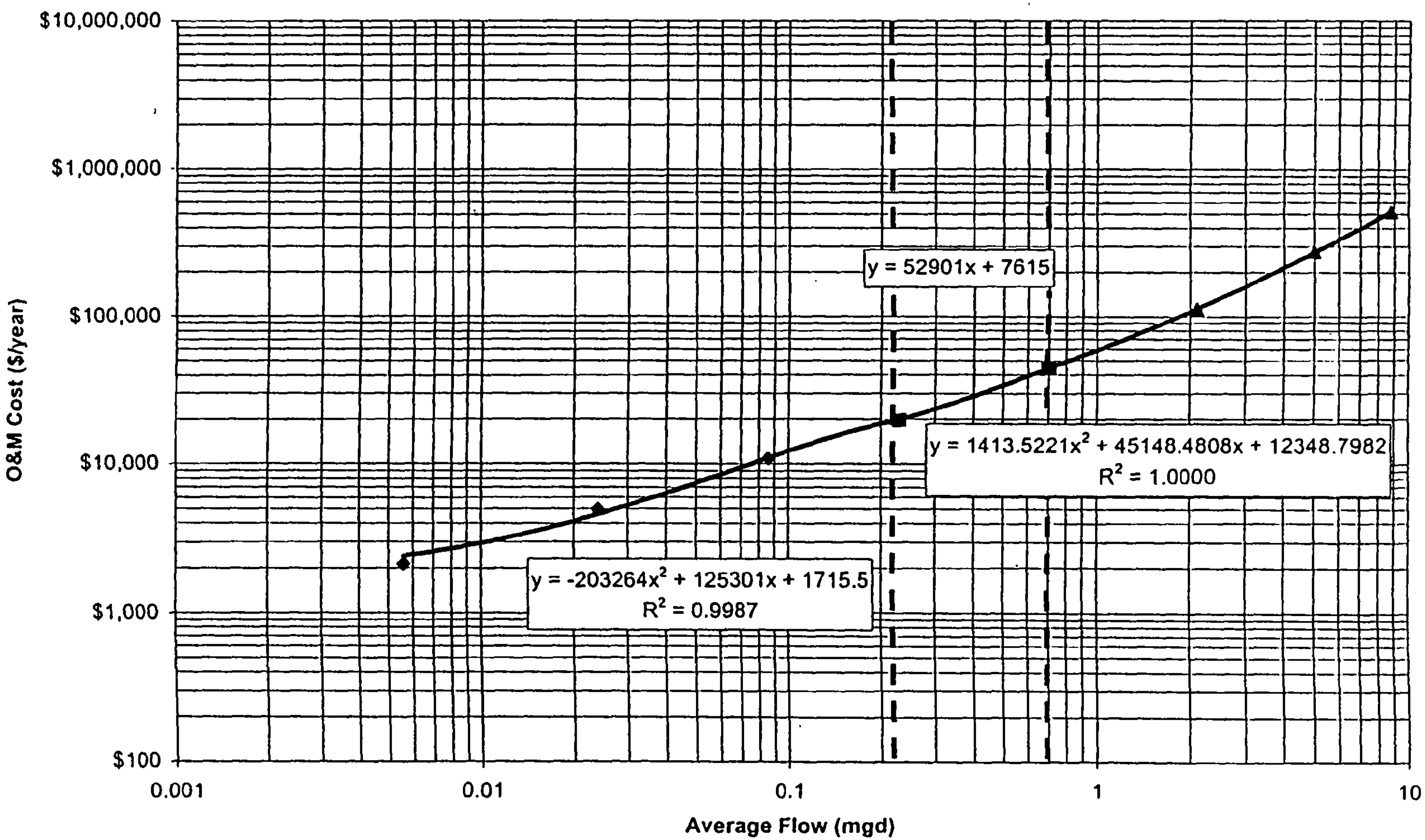


Figure 12-29
POTW Discharge - 500' of Pipe
Ion Exchange
Disposal Capital Costs

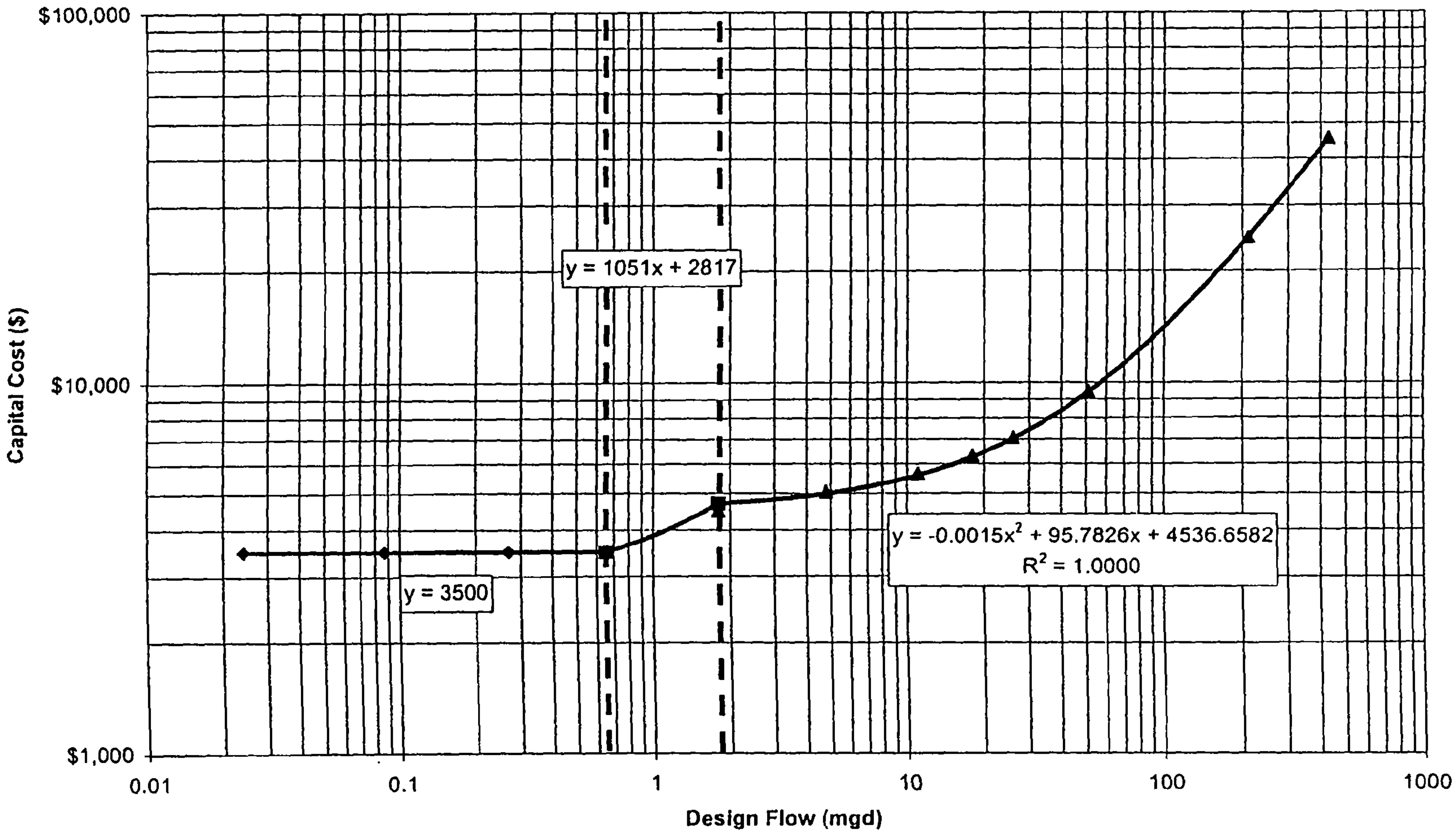


Figure 12-30
POTW - 500' of Pipe
Ion Exchange
Disposal O&M Costs

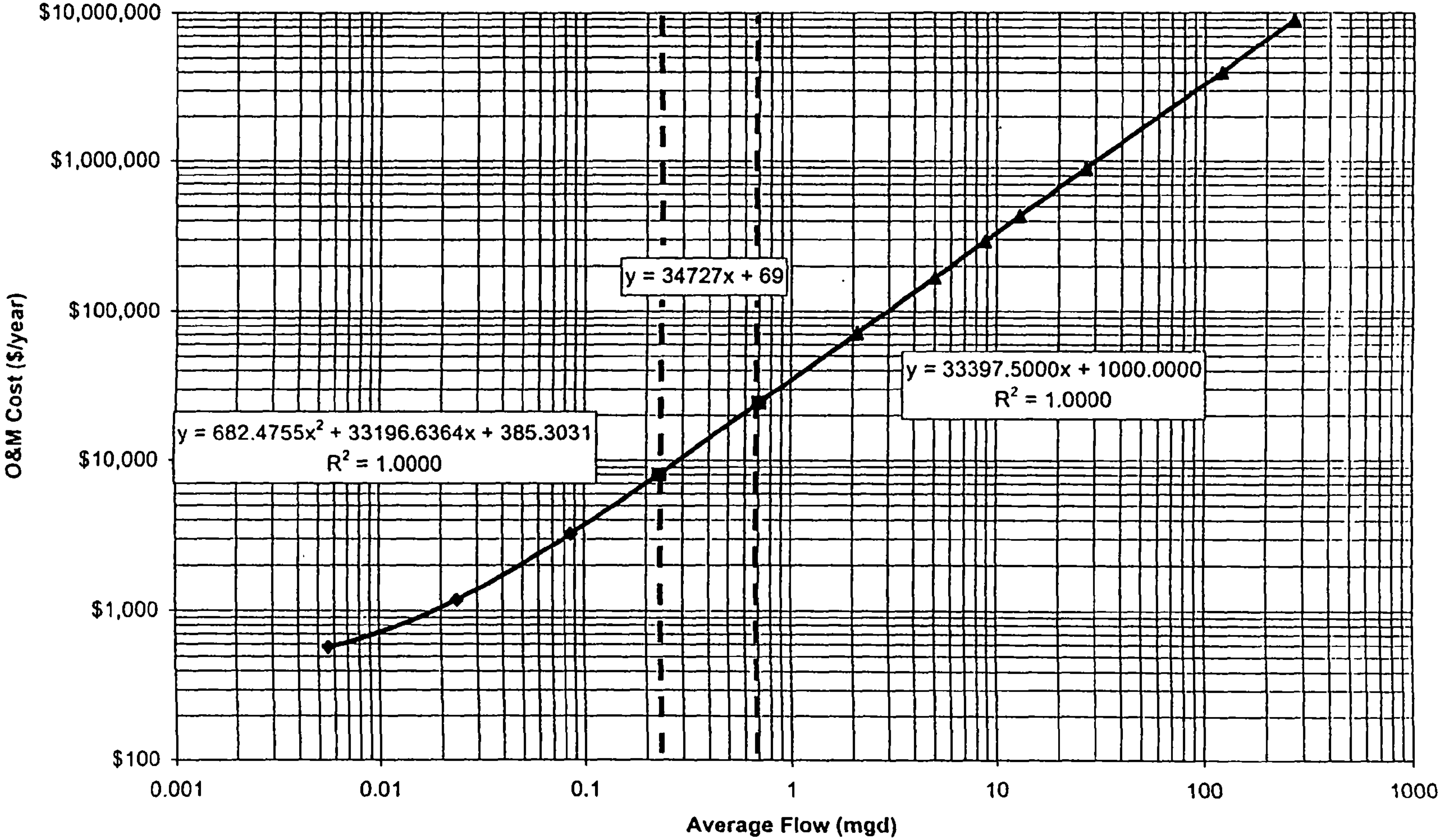


Figure 12-31
POTW Discharge - 1000' of Pipe
Ion Exchange
Disposal Capital Costs

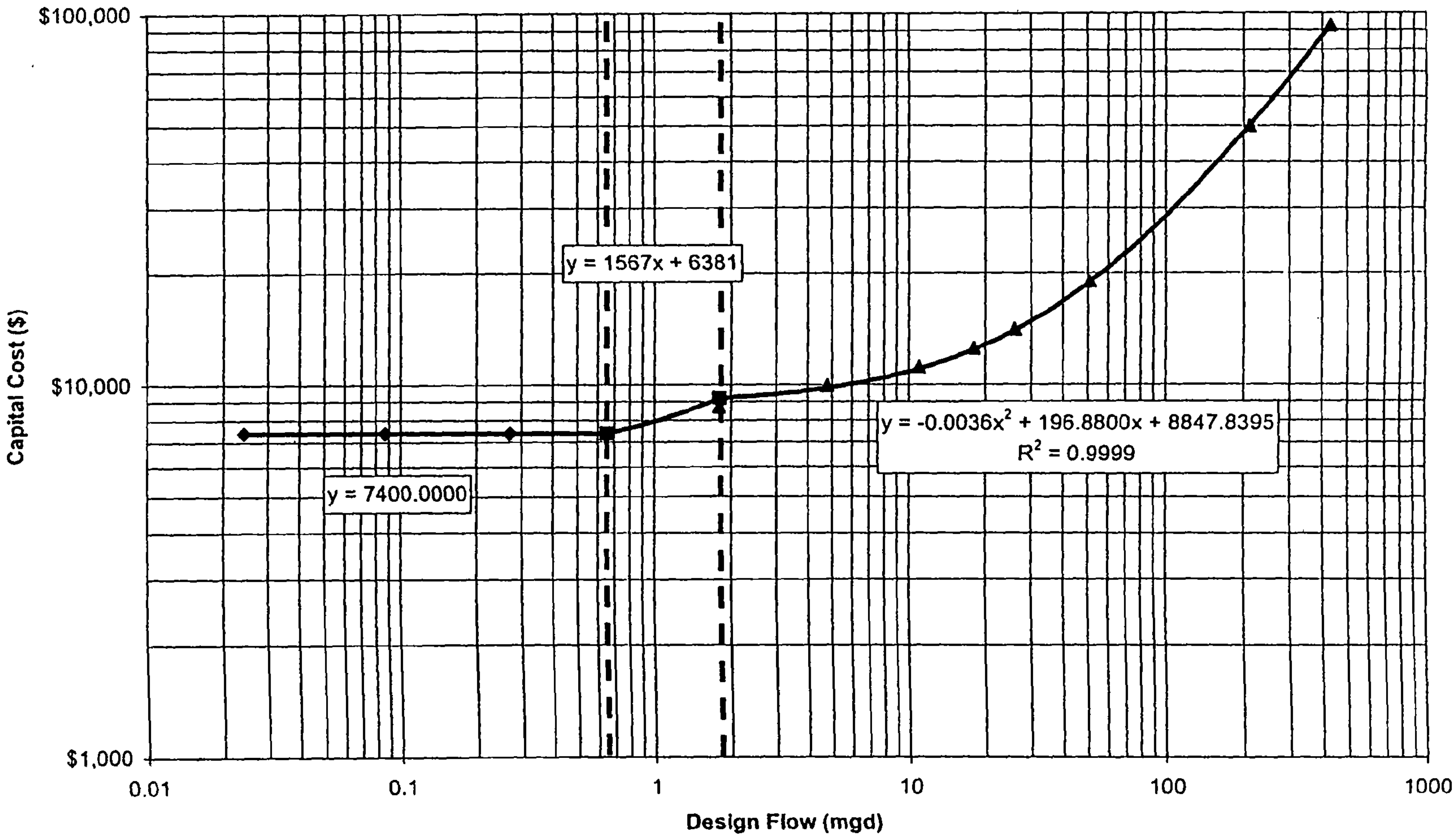


Figure 12-32
POTW - 1000' of Pipe
Ion Exchange
Disposal O&M Costs

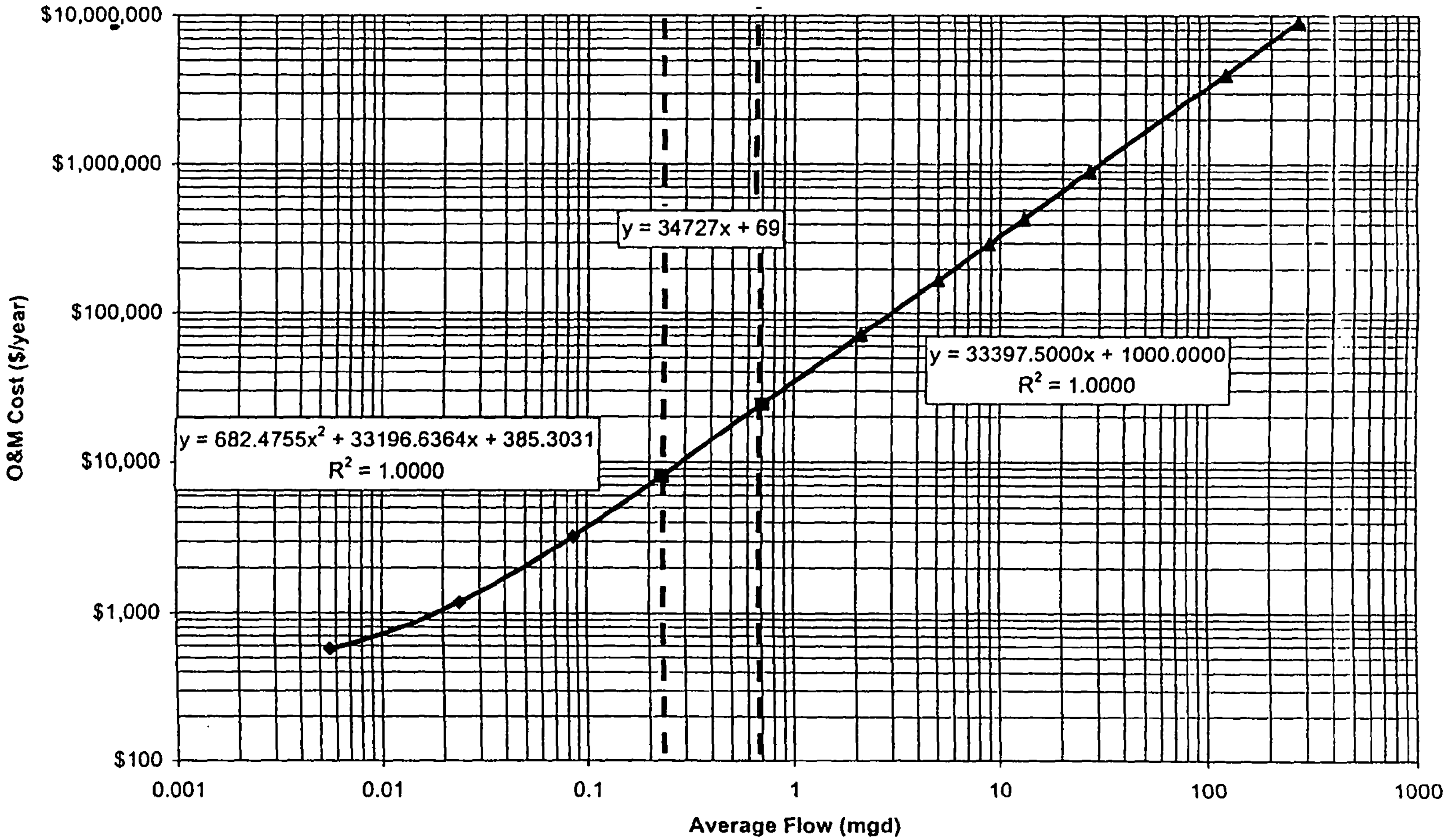


Figure 12-33
Chemical Precipitation
Reverse Osmosis
Disposal Capital Costs

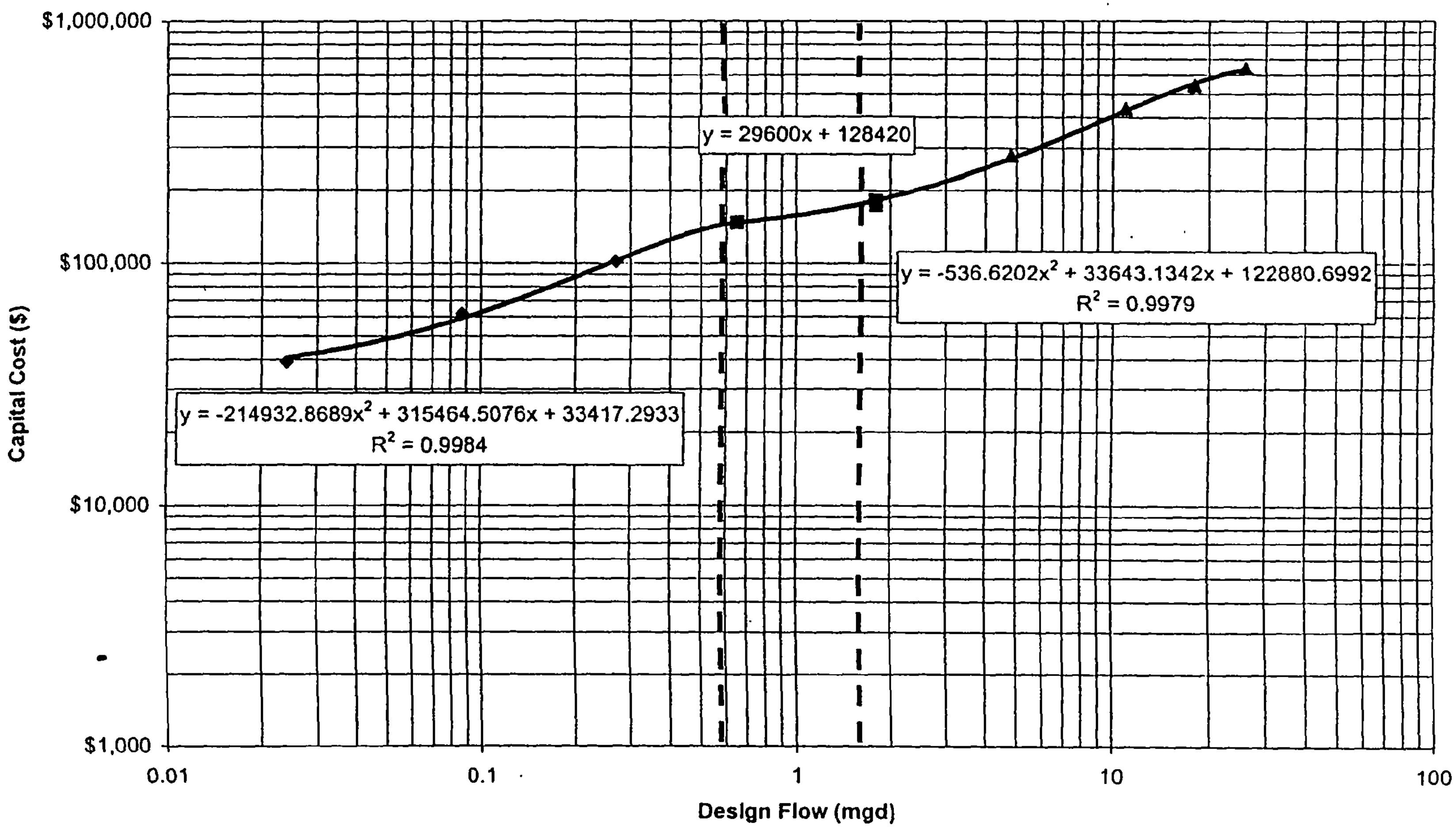


Figure 12-34
Chemical Precipitation
Reverse Osmosis
Disposal O&M Costs

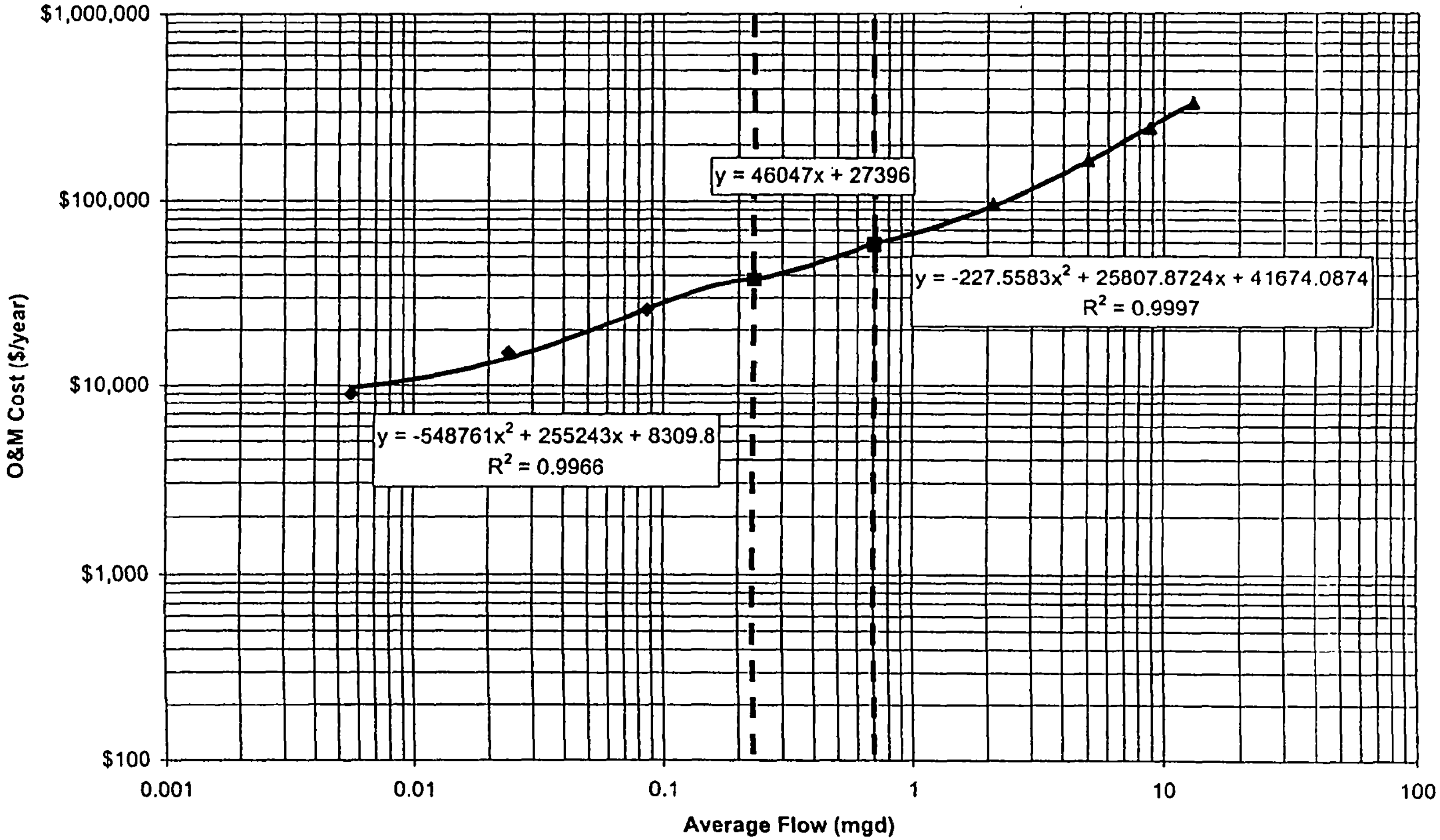


Figure 12-35
Direct Discharge - 500' of Pipe
Reverse Osmosis
Disposal Capital Costs

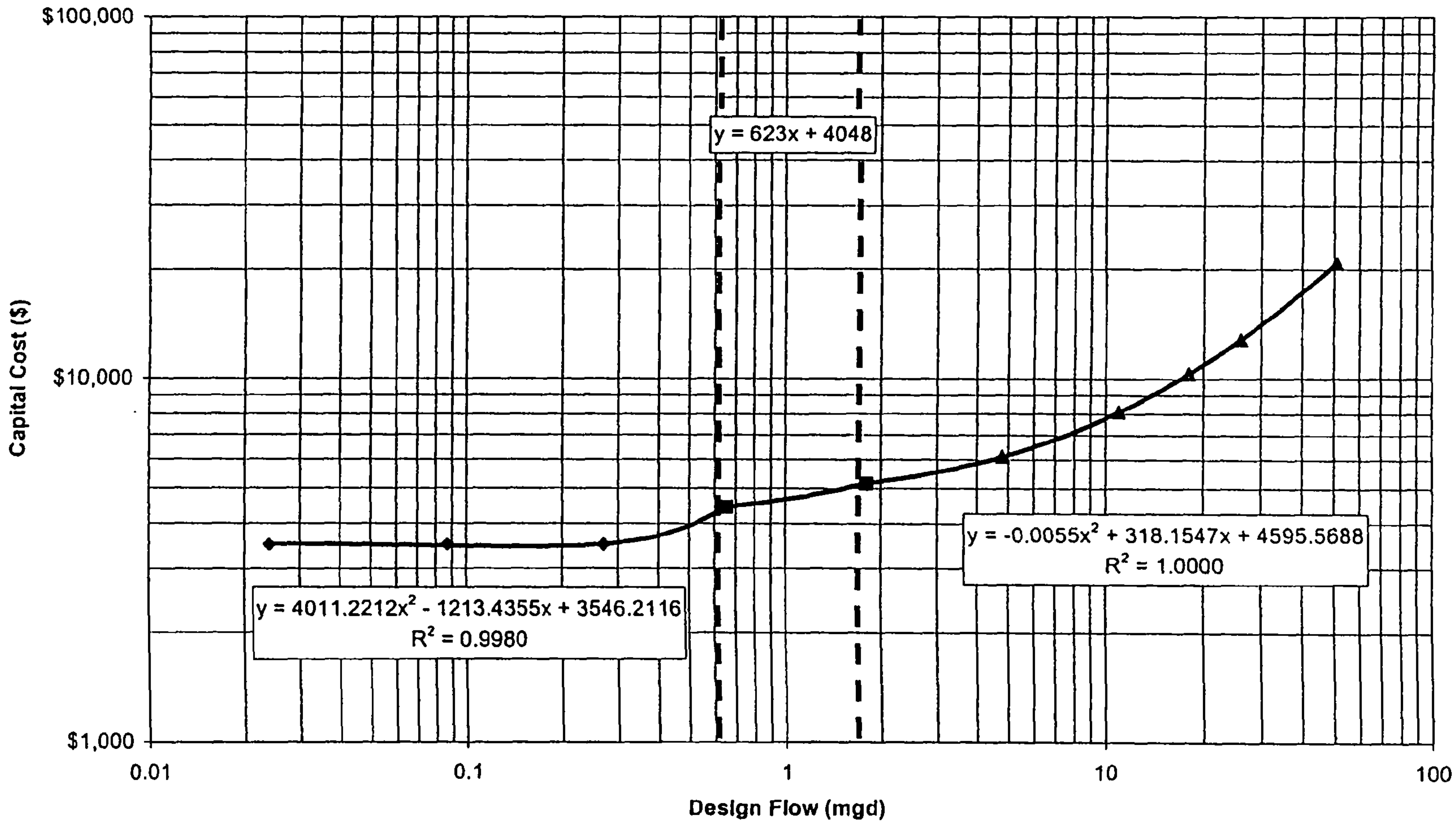


Figure 12-36
Direct Discharge - 500' of Pipe
Reverse Osmosis
Disposal O&M Costs

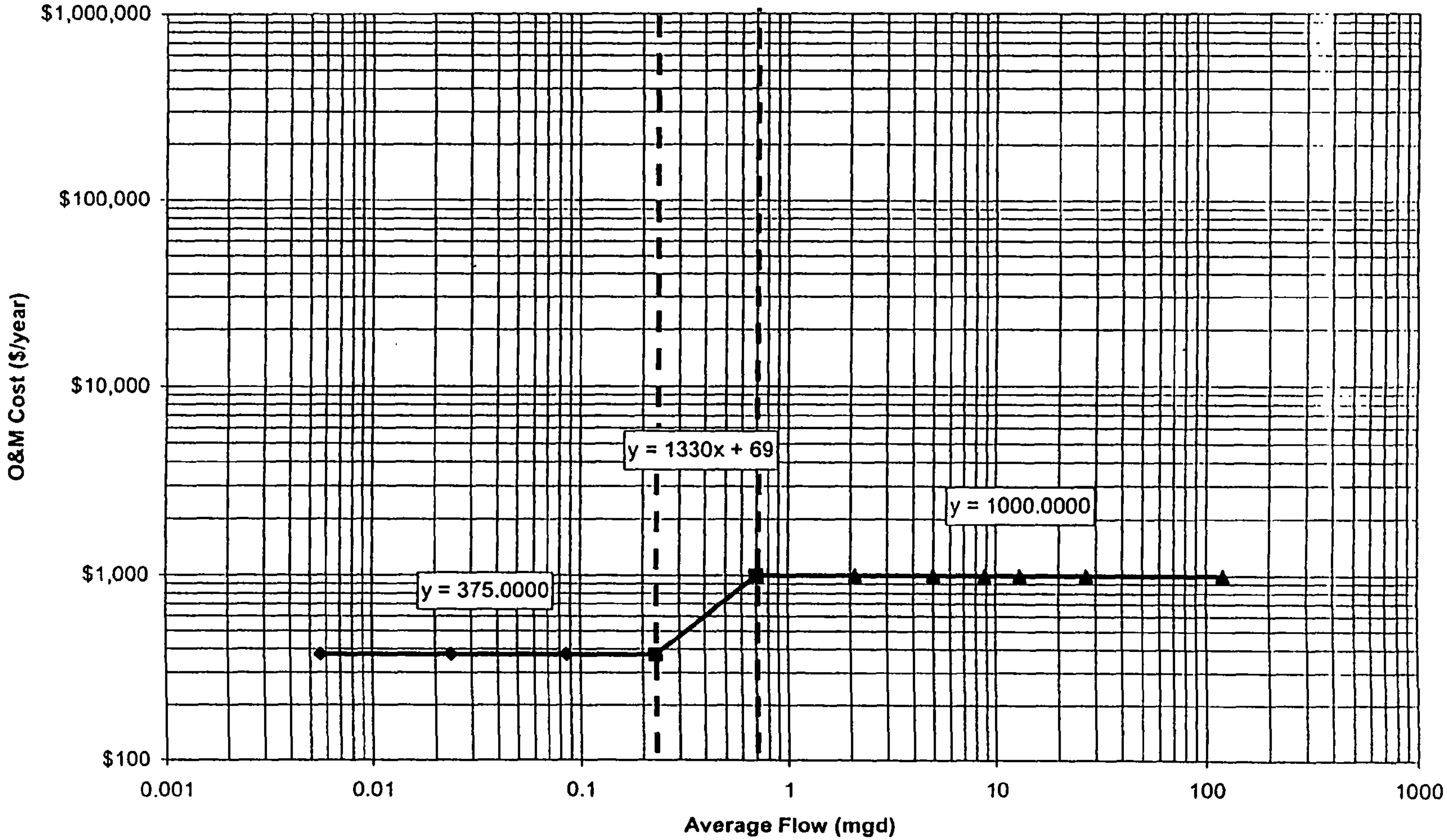


Figure 12-37
Direct Discharge - 1000' of Pipe
Reverse Osmosis
Disposal Capital Costs

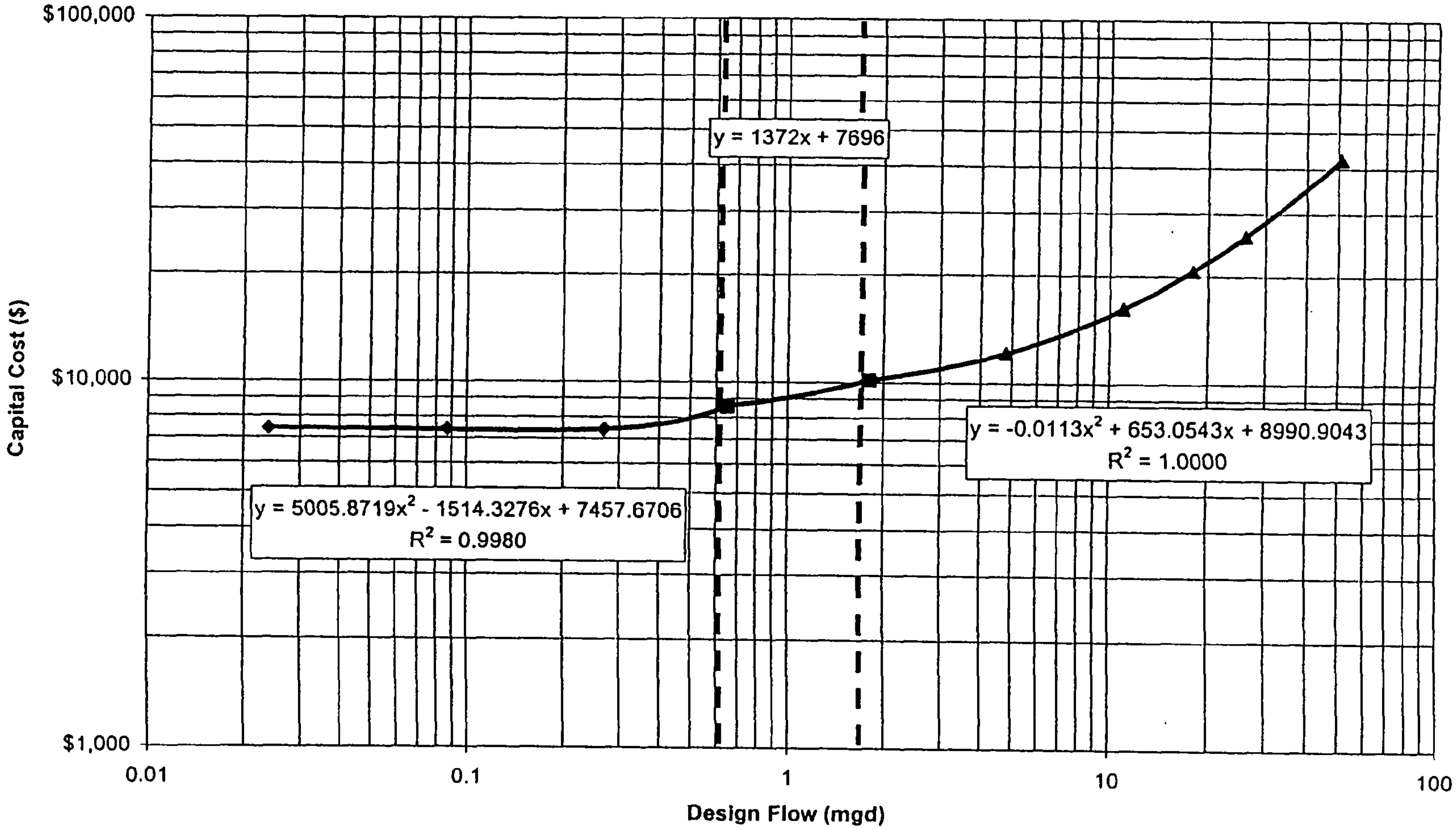


Figure 12-38
Direct Discharge - 1000' of Pipe
Reverse Osmosis
Disposal O&M Costs

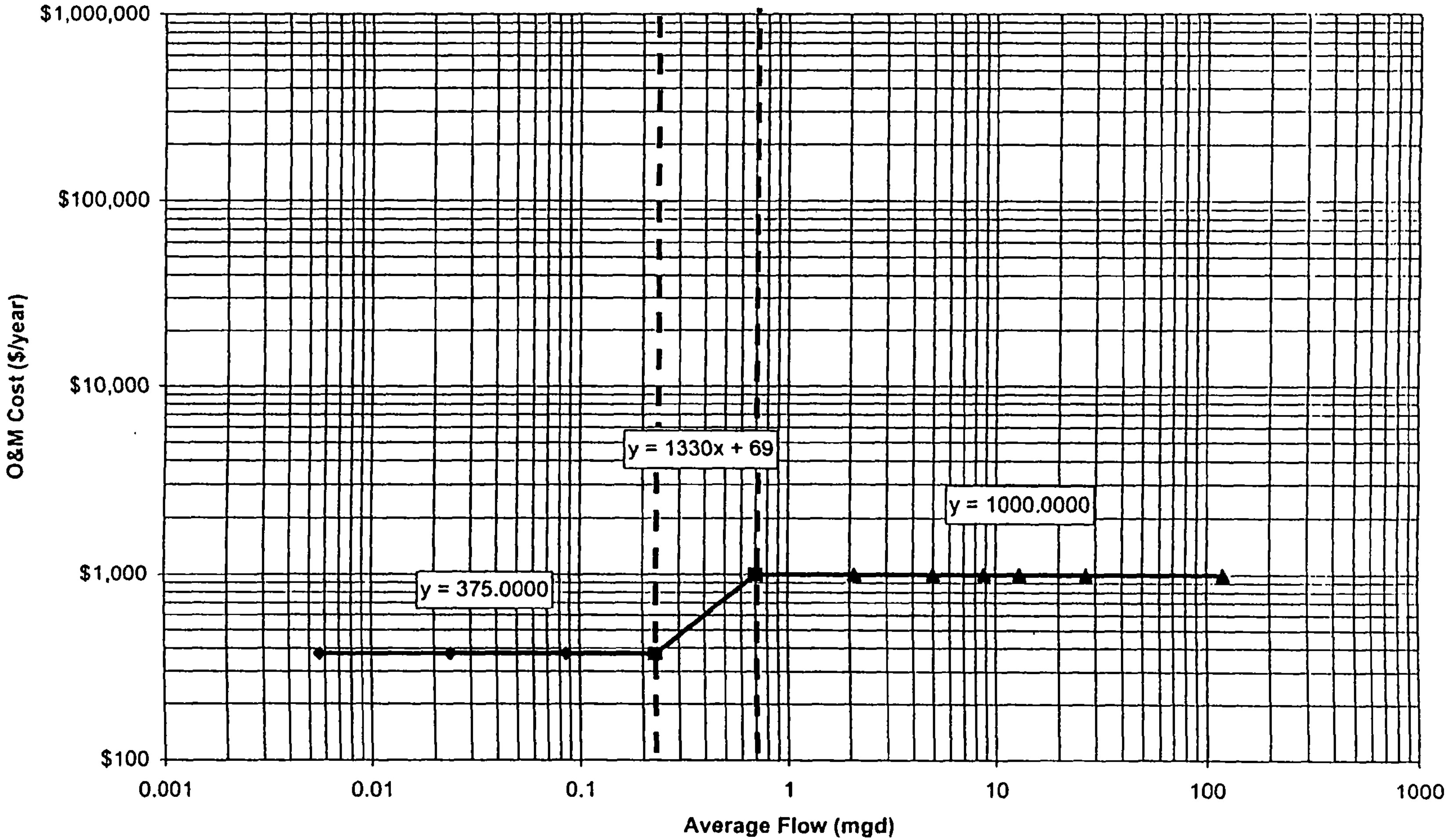


Figure 12-39
POTW Discharge - 500' of Pipe
Reverse Osmosis
Disposal Capital Costs

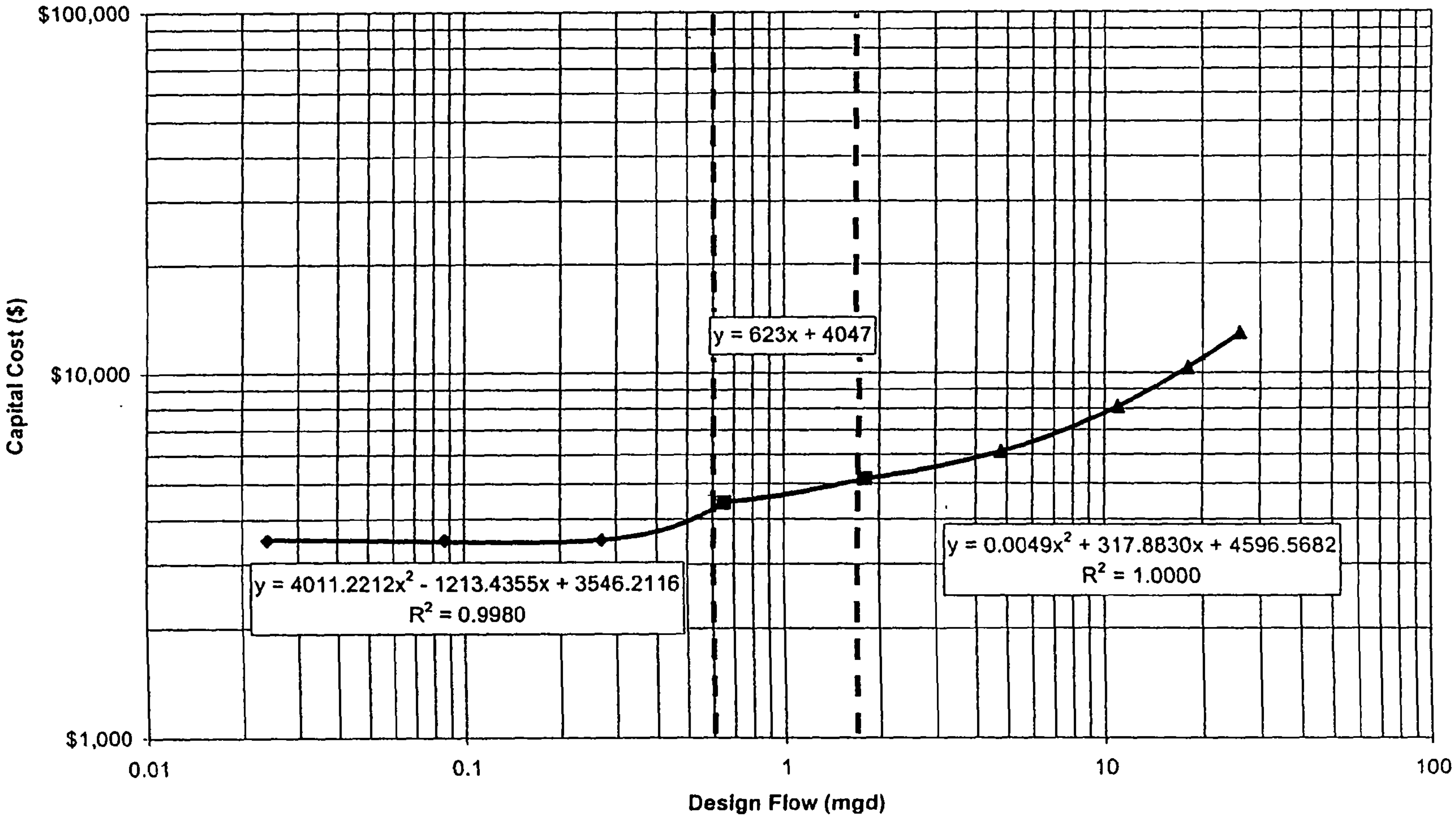


Figure 12-40
POTW Discharge - 500' of Pipe
Reverse Osmosis
Disposal O&M Costs

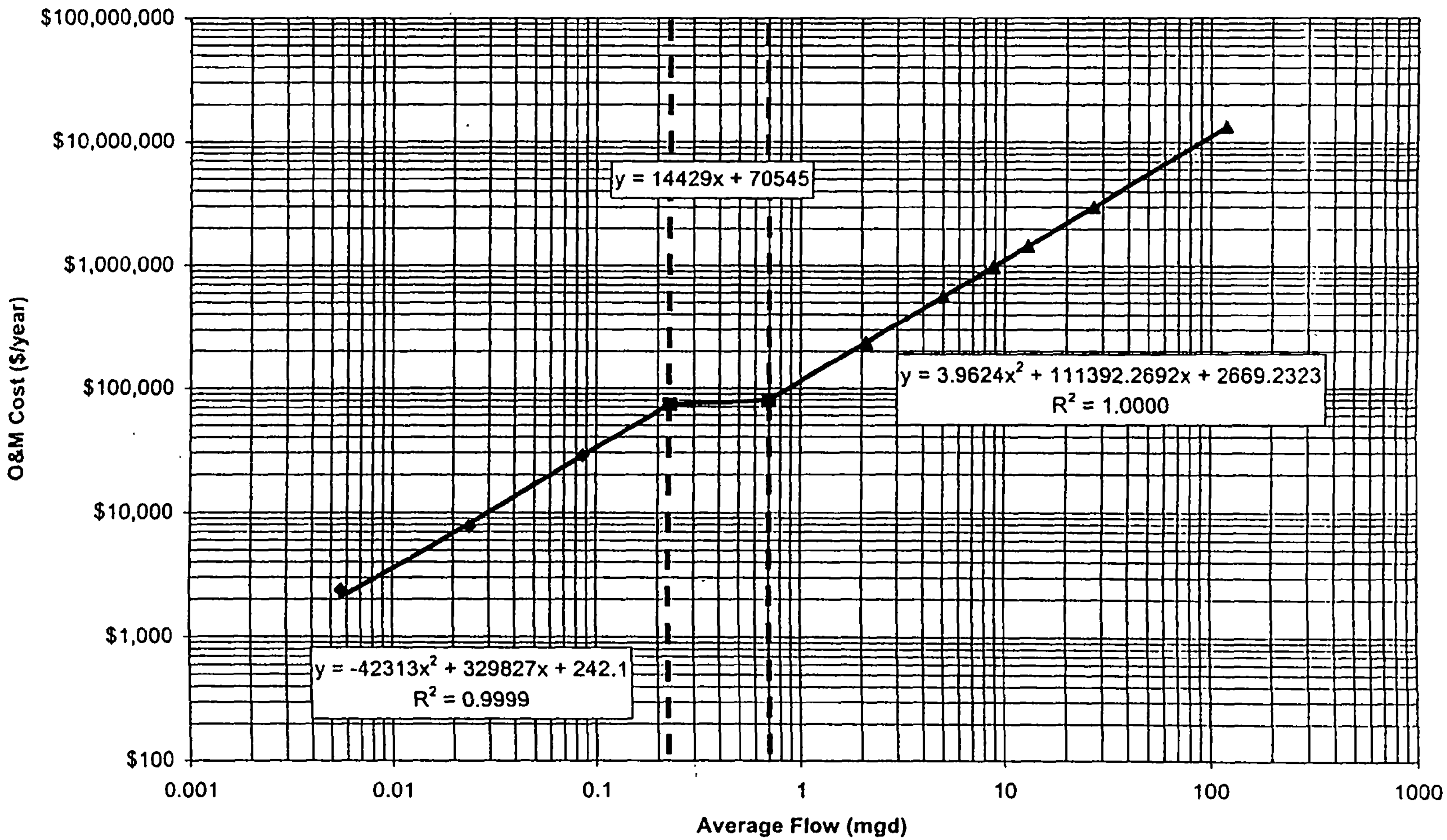


Figure 12-41
POTW Discharge - 1000' of Pipe
Reverse Osmosis
Disposal Capital Costs

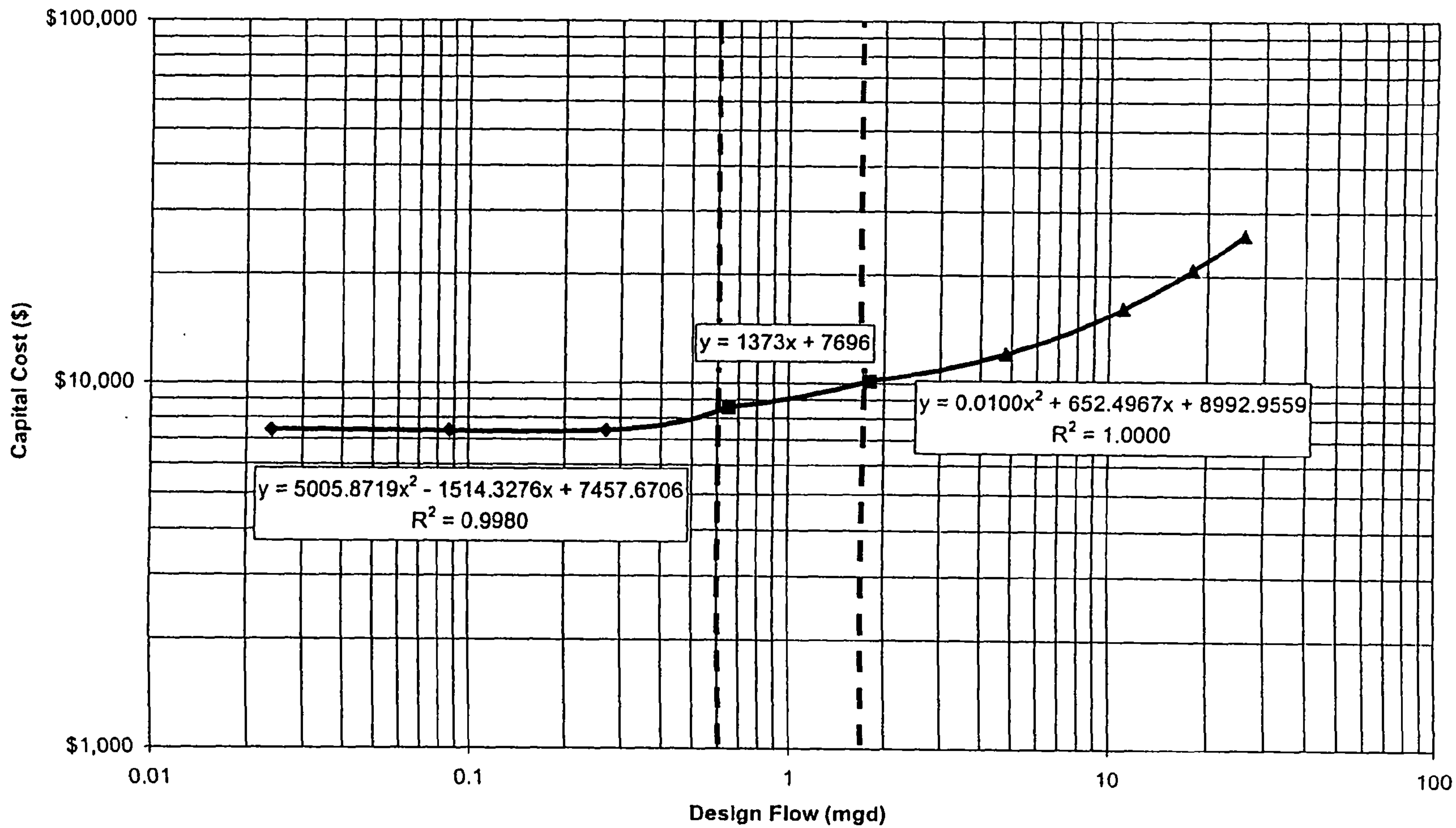
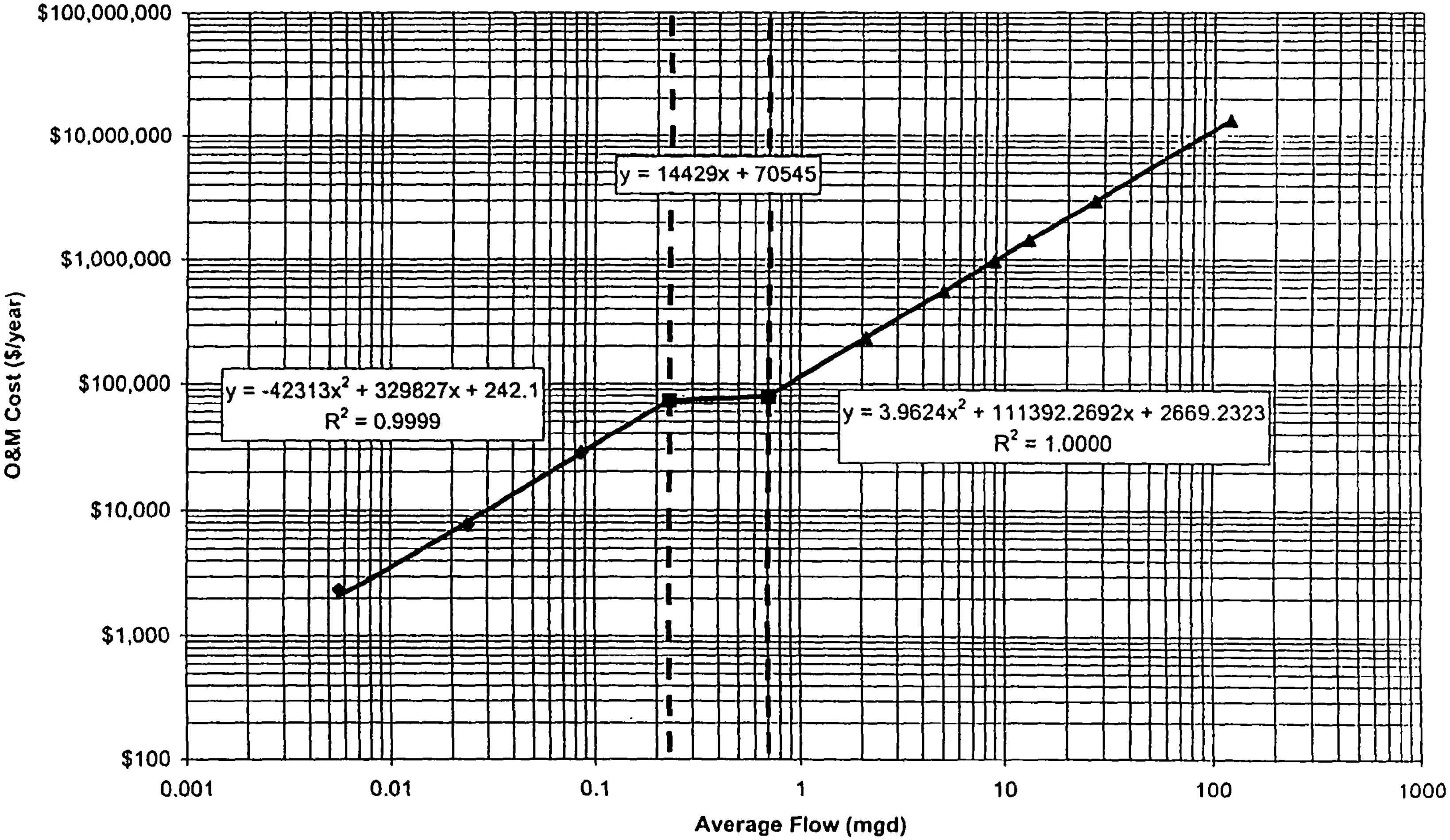


Figure 12-42
POTW Discharge - 1000' of Pipe
Reverse Osmosis
Disposal O&M Costs



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APPENDIX A

VERY SMALL SYSTEMS
CAPITAL COST BREAKDOWN SUMMARIES

Table A1 - VSS Document Capital Cost Breakdown for Membrane Processes

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	56.97%	p
Installation	0.2500	14.24%	c
Sitework/Interface Piping	0.0750	4.27%	c
Standby Power	0.0625	3.56%	c
OH&P	0.1665	9.49%	e
Legal & Admin	0.0416	2.37%	e
Engineering	0.1596	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.7552	100.00%	

Table A2 - VSS Document Capital Cost Breakdown for Ion Exchange Processes

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	54.78%	p
Installation	0.3000	16.43%	c
Sitework/Interface Piping	0.0780	4.27%	c
Standby Power	0.0650	3.56%	c
OH&P	0.1732	9.49%	e
Legal & Admin	0.0433	2.37%	e
Engineering	0.1659	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.8254	100.00%	

Table A3 - VSS Document Capital Cost Breakdown for Chlorination

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	61.93%	p
Installation	0.1500	9.29%	c
Sitework/Interface Piping	0.0690	4.27%	c
Standby Power	0.0575	3.56%	c
OH&P	0.1532	9.49%	e
Legal & Admin	0.0383	2.37%	e
Engineering	0.1468	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.6148	100.00%	

Table A4 - VSS Document Capital Cost Breakdown for Potassium Permanganate Feed

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	64.74%	p
Installation	0.1000	6.47%	c
Sitework/Interface Piping	0.0660	4.27%	c
Standby Power	0.0550	3.56%	c
OH&P	0.1465	9.49%	e
Legal & Admin	0.0366	2.37%	e
Engineering	0.1404	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.5446	100.00%	

Table A5 - Typical VSS Document Capital Cost Breakdown

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	54.78%	p
Installation	0.3000	16.43%	c
Sitework/Interface Piping	0.0780	4.27%	c
Standby Power	0.0650	3.56%	c
OH&P	0.1732	9.49%	e
Legal & Admin	0.0433	2.37%	e
Engineering	0.1659	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.8254	100.00%	

APPENDIX B

WATER MODEL
CAPITAL COST BREAKDOWN SUMMARIES

Table B1.1 - Base Costs Obtained from the Water Model for Activated Alumina

Cost Component	Contactor Volume (ft3)							Capital Cost Category
	32	71	126	283	385	502	754	
Excavation & Sitework	$4,700	$4,700	$4,700	$4,700	$4,700	$4,700	$4,700	c
Manufactured Equipment	$12,800	$23,900	$39,100	$50,600	$64,500	$72,900	$101,000	p
Activated Alumina	$1,400	$3,100	$5,400	$11,900	$15,400	$19,600	$29,400	p
Concrete	$400	$1,200	$1,800	$2,000	$2,500	$3,200	$4,100	p
Labor	$1,200	$1,500	$2,000	$2,800	$3,300	$3,400	$4,200	c
Pipes and Valves	$5,200	$6,500	$6,500	$8,400	$12,800	$13,300	$20,100	p
Electrical	$6,400	$6,400	$6,400	$8,000	$8,000	$8,500	$9,600	p
Housing	$8,700	$14,400	$16,900	$17,900	$24,800	$34,400	$43,900	p
Subtotal	$40,800	$61,700	$82,800	$106,300	$136,000	$160,000	$217,000	
Contingencies	$6,100	$9,300	$12,400	$15,900	$20,400	$24,000	$32,600	c
Total	$46,900	$71,000	$95,200	$122,200	$156,400	$184,000	$249,600	

Table B1.2 - Water Model Base Construction Cost Analysis for Activated Alumina

Cost Component	Contactor Volume (ft3)							Average Percent
	32	71	126	283	385	502	754	
Excavation & Sitework	10.02%	6.62%	4.94%	3.85%	3.01%	2.55%	1.88%	4.70%
Manufactured Equipment	27.29%	33.66%	41.07%	41.41%	41.24%	39.62%	40.46%	37.82%
Activated Alumina	2.99%	4.37%	5.67%	9.74%	9.85%	10.65%	11.78%	7.86%
Concrete	0.85%	1.69%	1.89%	1.64%	1.60%	1.74%	1.64%	1.58%
Labor	2.56%	2.11%	2.10%	2.29%	2.11%	1.85%	1.68%	2.10%
Pipes and Valves	11.09%	9.15%	6.83%	6.87%	8.18%	7.23%	8.05%	8.20%
Electrical	13.65%	9.01%	6.72%	6.55%	5.12%	4.62%	3.85%	7.07%
Housing	18.55%	20.28%	17.75%	14.65%	15.86%	18.70%	17.59%	17.62%
Contingencies	13.01%	13.10%	13.03%	13.01%	13.04%	13.04%	13.06%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B2.1 - Base Costs Obtained from the Water Model for Anion Exchange

Cost Component	Resin Volume (ft3)						Capital Cost Category
	4	17	54	188	280	520	
Excavation & Sitework	$2,100	$2,100	$4,400	$4,400	$4,400	$5,300	c
Manufactured Equipment	$3,100	$8,600	$23,100	$64,100	$96,800	$164,800	p
Concrete	$300	$400	$5,500	$5,800	$6,000	$8,400	p
Steel	$0	$0	$7,800	$7,800	$7,800	$10,900	p
Labor	$400	$1,100	$12,100	$12,800	$12,900	$17,200	c
Pipes and Valves	$800	$800	$1,000	$2,600	$2,600	$3,100	p
Electrical	$3,100	$3,100	$3,100	$3,100	$3,100	$3,100	p
Housing	$5,600	$9,600	$11,100	$16,600	$19,200	$25,000	p
Subtotal	$15,400	$25,700	$68,100	$117,200	$152,800	$237,800	
Contingencies	$2,300	$3,900	$10,200	$17,600	$22,900	$35,700	c
Total	$17,700	$29,600	$78,300	$134,800	$175,700	$273,500	

Table B2.2 - Water Model Base Construction Cost Analysis for Anion Exchange

Cost Component	Resin Volume (ft3)						Average Percent
	4	17	54	188	280	520	
Excavation & Sitework	11.86%	7.09%	5.62%	3.26%	2.50%	1.94%	5.38%
Manufactured Equipment	17.51%	29.05%	29.50%	47.55%	55.09%	60.26%	39.83%
Concrete	1.69%	1.35%	7.02%	4.30%	3.41%	3.07%	3.48%
Steel	0.00%	0.00%	9.96%	5.79%	4.44%	3.99%	4.03%
Labor	2.26%	3.72%	15.45%	9.50%	7.34%	6.29%	7.43%
Pipes and Valves	4.52%	2.70%	1.28%	1.93%	1.48%	1.13%	2.17%
Electrical	17.51%	10.47%	3.96%	2.30%	1.76%	1.13%	6.19%
Housing	31.64%	32.43%	14.18%	12.31%	10.93%	9.14%	18.44%
Contingencies	12.99%	13.18%	13.03%	13.06%	13.03%	13.05%	13.06%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B3.1 - Base Costs Obtained from the Water Model for Basic Chemical Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	0.1-10	25	50	100	250	500	1000	
Dissolving Tank	$290	$430	$640	$910	$1,830	$2,200	$4,400	p
Mixer	$180	$200	$200	$240	$410	$620	$620	p
Metering Pump	$430	$700	$750	$1,230	$1,600	$1,670	$1,820	p
Pipes and Valves	$180	$180	$220	$220	$280	$280	$420	p
Labor	$180	$180	$240	$260	$300	$330	$400	c
Electrical	$80	$100	$150	$200	$250	$300	$400	p
Subtotal	$1,340	$1,790	$2,200	$3,060	$4,670	$5,400	$8,060	
Contingencies	$200	$270	$330	$460	$700	$810	$1,210	c
Total	$1,540	$2,060	$2,530	$3,520	$5,370	$6,210	$9,270	

Table B3.2 - Water Model Base Construction Cost Analysis for Basic Chemical Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	0.1-10	25	50	100	250	500	1000	
Dissolving Tank	18.83%	20.87%	25.30%	25.85%	34.08%	35.43%	47.46%	29.69%
Mixer	11.69%	9.71%	7.91%	6.82%	7.64%	9.98%	6.69%	8.63%
Metering Pump	27.92%	33.98%	29.64%	34.94%	29.80%	26.89%	19.63%	28.97%
Pipes and Valves	11.69%	8.74%	8.70%	6.25%	5.21%	4.51%	4.53%	7.09%
Labor	11.69%	8.74%	9.49%	7.39%	5.59%	5.31%	4.31%	7.50%
Electrical	5.19%	4.85%	5.93%	5.68%	4.66%	4.83%	4.31%	5.07%
Contingencies	12.99%	13.11%	13.04%	13.07%	13.04%	13.04%	13.05%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B4.1 - Base Costs Obtained from the Water Model for Chlorination

Cost Component	Cost	Capital Cost Category
Excavation & Sitework	$1,200	c
Manufactured Equipment	$2,700	p
Concrete	$300	p
Labor	$400	c
Pipes and Valves	$500	p
Electrical	$2,200	p
Housing	$7,800	p
Subtotal	$15,100	
Contingencies	$2,300	c
Total	$17,400	

Table B4.2 - Water Model Base Construction Cost Analysis for Chlorination

Cost Component	Cost	Average Percent
Excavation & Sitework	6.90%	6.90%
Manufactured Equipment	15.52%	15.52%
Concrete	1.72%	1.72%
Labor	2.30%	2.30%
Pipes and Valves	2.87%	2.87%
Electrical	12.64%	12.64%
Housing	44.83%	44.83%
Contingencies	13.22%	13.22%
Total	100.00%	100.00%

Table B5.1 - Base Costs Obtained from the Water Model for Underground Clearwell Storage

Cost Component	Design Capacity (gpd)					Capital Cost Category
	5,000	10,000	50,000	100,000	500,000	
Excavation & Sitework	$3,300	$5,700	$16,500	$25,300	$75,400	c
Concrete	$9,800	$16,500	$37,000	$64,000	$216,400	p
Steel	$300	$400	$500	$500	$600	p
Electrical	$2,600	$2,600	$2,600	$2,600	$2,600	p
Subtotal	$16,000	$25,200	$56,600	$92,400	$295,000	
Contingencies	$2,400	$3,800	$8,500	$13,900	$44,300	c
Total	$18,400	$29,000	$65,100	$106,300	$339,300	

Table B5.2 - Water Model Base Construction Cost Analysis for Underground Clearwell Storage

Cost Component	Design Capacity (gpd)					Average Percent
	5,000	10,000	50,000	100,000	500,000	
Excavation & Sitework	17.93%	19.66%	25.35%	23.80%	22.22%	21.79%
Concrete	53.26%	56.90%	56.84%	60.21%	63.78%	58.20%
Steel	1.63%	1.38%	0.77%	0.47%	0.18%	0.88%
Electrical	14.13%	8.97%	3.99%	2.45%	0.77%	6.06%
Contingencies	13.04%	13.10%	13.06%	13.08%	13.06%	13.07%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B6.1 - Base Costs Obtained from the Water Model for Package Conventional Treatment

Cost Component	Filter Area (ft2)						Capital Cost Category
	2	12	20	40	112	150	
Excavation & Sitework	$3,500	$3,500	$4,700	$5,800	$7,000	$9,300	c
Manufactured Equipment	$31,000	$44,900	$53,500	$111,300	$176,600	$190,500	p
Concrete	$1,000	$1,000	$1,500	$4,500	$5,700	$6,800	p
Labor	$9,900	$14,700	$17,500	$36,400	$57,800	$62,400	c
Pipes and Valves	$4,200	$8,300	$10,400	$20,900	$29,200	$41,700	p
Electrical	$3,200	$4,500	$5,300	$11,100	$17,600	$19,000	p
Housing	$18,600	$18,600	$23,400	$45,000	$47,500	$52,500	p
Subtotal	$71,400	$95,500	$116,300	$235,000	$341,400	$382,200	
Contingencies	$10,700	$14,300	$17,400	$35,300	$51,200	$57,300	c
Total	$82,100	$109,800	$133,700	$270,300	$392,600	$439,500	

Table B6.2 - Water Model Base Construction Cost Analysis for Package Conventional Treatment

Cost Component	Filter Area (ft2)						Average Percent
	2	12	20	40	112	150	
Excavation & Sitework	4.26%	3.19%	3.52%	2.15%	1.78%	2.12%	2.84%
Manufactured Equipment	37.76%	40.89%	40.01%	41.18%	44.98%	43.34%	41.36%
Concrete	1.22%	0.91%	1.12%	1.66%	1.45%	1.55%	1.32%
Labor	12.06%	13.39%	13.09%	13.47%	14.72%	14.20%	13.49%
Pipes and Valves	5.12%	7.56%	7.78%	7.73%	7.44%	9.49%	7.52%
Electrical	3.90%	4.10%	3.96%	4.11%	4.48%	4.32%	4.15%
Housing	22.66%	16.94%	17.50%	16.65%	12.10%	11.95%	16.30%
Contingencies	13.03%	13.02%	13.01%	13.06%	13.04%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B7.1 - Base Costs Obtained from the Water Model for Ferric Chloride Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	1	10	25	50	100	250	750	
Storage Tank	$0	$0	$0	$0	$360	$780	$2,040	p
Wooden Stairway	$0	$0	$0	$0	$0	$300	$300	p
Metering Pump	$390	$390	$390	$390	$390	$1,090	$1,100	p
Pipes and Valves	$180	$180	$180	$180	$220	$280	$280	p
Labor	$120	$120	$130	$130	$210	$360	$410	c
Electrical	$80	$80	$80	$80	$100	$120	$120	p
Subtotal	$770	$770	$780	$780	$1,280	$2,930	$4,250	
Contingencies	$120	$120	$120	$120	$190	$440	$640	c
Total	$890	$890	$900	$900	$1,470	$3,370	$4,890	

Table B7.2 - Water Model Base Construction Cost Analysis for Ferric Chloride Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	1	10	25	50	100	250	750	
Storage Tank	0.00%	0.00%	0.00%	0.00%	24.49%	23.15%	41.72%	12.76%
Wooden Stairway	0.00%	0.00%	0.00%	0.00%	0.00%	8.90%	6.13%	2.15%
Metering Pump	43.82%	43.82%	43.33%	43.33%	26.53%	32.34%	22.49%	36.53%
Pipes and Valves	20.22%	20.22%	20.00%	20.00%	14.97%	8.31%	5.73%	15.64%
Labor	13.48%	13.48%	14.44%	14.44%	14.29%	10.68%	8.38%	12.74%
Electrical	8.99%	8.99%	8.89%	8.89%	6.80%	3.56%	2.45%	6.94%
Contingencies	13.48%	13.48%	13.33%	13.33%	12.93%	13.06%	13.09%	13.24%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B8.1 - Base Costs Obtained from the Water Model for Package Lime Softening

Cost Component	Design Capacity (gpd)					Capital Cost Category
	15,000	150,000	430,000	750,000	1,000,000	
Excavation & Sitework	$3,500	$5,800	$6,700	$8,400	$9,800	c
Manufactured Equipment	$33,200	$49,800	$66,300	$86,200	$103,800	p
Concrete	$1,100	$2,500	$3,200	$5,900	$7,000	p
Labor	$14,000	$18,200	$28,000	$36,400	$43,800	c
Pipes and Valves	$5,200	$10,400	$14,100	$16,700	$45,900	p
Electrical	$8,500	$12,200	$17,000	$18,900	$26,700	p
Housing	$8,800	$16,400	$19,800	$30,000	$33,000	p
Subtotal	$74,300	$115,300	$155,100	$202,500	$270,000	
Contingencies	$11,100	$17,300	$23,300	$30,400	$40,500	c
Total	$85,400	$132,600	$178,400	$232,900	$310,500	

Table B8.2 - Water Model Base Construction Cost Analysis for Package Lime Softening

Cost Component	Design Capacity (gpd)					Average Percent
	15,000	150,000	430,000	750,000	1,000,000	
Excavation & Sitework	4.10%	4.37%	3.76%	3.61%	3.16%	3.80%
Manufactured Equipment	38.88%	37.56%	37.16%	37.01%	33.43%	36.81%
Concrete	1.29%	1.89%	1.79%	2.53%	2.25%	1.95%
Labor	16.39%	13.73%	15.70%	15.63%	14.11%	15.11%
Pipes and Valves	6.09%	7.84%	7.90%	7.17%	14.78%	8.76%
Electrical	9.95%	9.20%	9.53%	8.12%	8.60%	9.08%
Housing	10.30%	12.37%	11.10%	12.88%	10.63%	11.46%
Contingencies	13.00%	13.05%	13.06%	13.05%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B9.1 - Base Costs Obtained from the Water Model for Permanganate Feed

Cost Component	Maximum Feed Rate (lb/day)						Capital Cost Category
	0.5-5	12.5	25	50	125	250	
Dissolving Tank	$290	$430	$640	$910	$1,830	$2,200	p
Mixer	$180	$200	$200	$240	$410	$620	p
Metering Pump	$430	$700	$750	$1,230	$1,600	$1,670	p
Pipes and Valves	$180	$180	$220	$220	$280	$280	p
Labor	$180	$180	$240	$260	$300	$330	c
Electrical	$80	$100	$150	$200	$250	$300	p
Subtotal	$1,340	$1,790	$2,200	$3,060	$4,670	$5,400	
Contingencies	$200	$270	$330	$460	$700	$810	c
Total	$1,540	$2,060	$2,530	$3,520	$5,370	$6,210	

Table B9.2 - Water Model Base Construction Cost Analysis for Permanganate Feed

Cost Component	Maximum Feed Rate (lb/day)						Average Percent
	0.5-5	12.5	25	50	125	250	
Excavation & Sitework	18.83%	20.87%	25.30%	25.85%	34.08%	35.43%	26.73%
Manufactured Equipment	11.69%	9.71%	7.91%	6.82%	7.64%	9.98%	8.96%
Concrete	27.92%	33.98%	29.64%	34.94%	29.80%	26.89%	30.53%
Labor	11.69%	8.74%	8.70%	6.25%	5.21%	4.51%	7.52%
Pipes and Valves	11.69%	8.74%	9.49%	7.39%	5.59%	5.31%	8.03%
Electrical	5.19%	4.85%	5.93%	5.68%	4.66%	4.83%	5.19%
Contingencies	12.99%	13.11%	13.04%	13.07%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B10.1 - Base Costs Obtained from the Water Model for Polymer Feed

Cost Component	Maximum Feed Rate (lb/day)					Capital Cost Category
	0.6	1	2.1	4.2	10.4	
Mixing Tank	$290	$430	$640	$910	$1,830	p
Mixer	$850	$850	$200	$1,050	$1,050	p
Metering Pump	$640	$700	$750	$1,230	$1,600	p
Pipes and Valves	$180	$180	$220	$220	$280	p
Labor	$180	$180	$240	$260	$300	c
Electrical	$80	$100	$150	$200	$250	p
Subtotal	$2,220	$2,440	$2,200	$3,870	$5,310	
Contingencies	$330	$370	$330	$580	$800	c
Total	$2,550	$2,810	$2,530	$4,450	$6,110	

Table B10.2 - Water Model Base Construction Cost Analysis for Polymer Feed

Cost Component	Maximum Feed Rate (lb/day)					Average Percent
	0.6	1	2.1	4.2	10.4	
Mixing Tank	11.37%	15.30%	25.30%	20.45%	29.95%	20.47%
Mixer	33.33%	30.25%	7.91%	23.60%	17.18%	22.45%
Metering Pump	25.10%	24.91%	29.64%	27.64%	26.19%	26.70%
Pipes and Valves	7.06%	6.41%	8.70%	4.94%	4.58%	6.34%
Labor	7.06%	6.41%	9.49%	5.84%	4.91%	6.74%
Electrical	3.14%	3.56%	5.93%	4.49%	4.09%	4.24%
Contingencies	12.94%	13.17%	13.04%	13.03%	13.09%	13.06%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B11.1 - Base Costs Obtained from the Water Model for Raw Water Pumping

Cost Component	Design Capacity (gpd)					Capital Cost Category
	28,800	144,000	504,000	720,000	1,008,000	
Excavation & Sitework	$11,700	$11,700	$12,300	$12,300	$12,800	c
Manufactured Equipment	$6,600	$7,800	$11,800	$12,600	$16,500	p
Concrete	$500	$500	$1,100	$1,100	$1,500	p
Labor	$3,700	$3,800	$5,800	$6,200	$8,500	c
Pipes and Valves	$1,500	$1,800	$2,700	$3,600	$4,500	p
Electrical	$800	$800	$1,400	$1,600	$2,100	p
Subtotal	$24,800	$26,400	$35,100	$37,400	$45,900	
Contingencies	$3,700	$4,000	$5,300	$5,600	$6,900	c
Total	$28,500	$30,400	$40,400	$43,000	$52,800	

Table B11.2 - Water Model Base Construction Cost Analysis for Raw Water Pumping

Cost Component	Design Capacity (gpd)					Average Percent
	28,800	144,000	504,000	720,000	1,008,000	
Excavation & Sitework	41.05%	38.49%	30.45%	28.60%	24.24%	32.57%
Manufactured Equipment	23.16%	25.66%	29.21%	29.30%	31.25%	27.72%
Concrete	1.75%	1.64%	2.72%	2.56%	2.84%	2.30%
Labor	12.98%	12.50%	14.36%	14.42%	16.10%	14.07%
Pipes and Valves	5.26%	5.92%	6.68%	8.37%	8.52%	6.95%
Electrical	2.81%	2.63%	3.47%	3.72%	3.98%	3.32%
Contingencies	12.98%	13.16%	13.12%	13.02%	13.07%	13.07%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B12.1 - Base Costs Obtained from the Water Model for Package Reverse Osmosis

Cost Component	Plant Capacity (gpd)						Capital Cost Category
	2,500	10,000	50,000	100,000	500,000	1,000,000	
Manufactured Equipment	$20,300	$30,000	$69,600	$123,000	$454,800	$877,400	p
Labor	$800	$1,200	$1,500	$2,800	$7,500	$14,600	c
Electrical	$3,200	$4,600	$10,700	$18,700	$45,900	$62,100	p
Housing	$11,900	$13,900	$16,400	$18,500	$38,400	$52,500	p
Subtotal	$36,200	$49,700	$98,200	$163,000	$546,600	$1,006,600	
Contingencies	$5,400	$7,500	$14,700	$24,500	$82,000	$151,000	c
Total	$41,600	$57,200	$112,900	$187,500	$628,600	$1,157,600	

Table B12.2 - Water Model Base Construction Cost Analysis for Package Reverse Osmosis

Cost Component	Plant Capacity (gpd)						Average Percent
	2,500	10,000	50,000	100,000	500,000	1,000,000	
Manufactured Equipment	48.80%	52.45%	61.65%	65.60%	72.35%	75.79%	62.77%
Labor	1.92%	2.10%	1.33%	1.49%	1.19%	1.26%	1.55%
Electrical	7.69%	8.04%	9.48%	9.97%	7.30%	5.36%	7.98%
Housing	28.61%	24.30%	14.53%	9.87%	6.11%	4.54%	14.66%
Contingencies	12.98%	13.11%	13.02%	13.07%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B13.1 - Base Costs Obtained from the Water Model for Sodium Hydroxide Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	0.8	4	8	42	83	417	834	
Storage and Feed Tanks	$60	$60	$90	$970	$2,040	$3,560	$6,940	p
Heating and Insulation	$0	$0	$0	$200	$410	$950	$1,620	p
Mixer	$0	$0	$0	$180	$240	$620	$640	p
Stairway	$0	$0	$0	$0	$0	$300	$600	p
Man. Transfer Pump	$100	$100	$100	$0	$0	$0	$0	p
Pipes and Valves	$310	$310	$310	$470	$470	$530	$790	p
Metering Pump	$390	$390	$390	$390	$410	$1,090	$1,100	p
Containment Wall	$120	$120	$150	$270	$400	$600	$880	p
Labor	$280	$280	$280	$420	$480	$650	$860	c
Electrical	$80	$80	$80	$100	$100	$120	$120	p
Subtotal	$1,340	$1,340	$1,400	$3,000	$4,550	$8,420	$13,550	
Contingencies	$200	$200	$210	$450	$680	$1,260	$2,030	c
Total	$1,540	$1,540	$1,610	$3,450	$5,230	$9,680	$15,580	

Table B13.2 - Water Model Base Construction Cost Analysis for Sodium Hydroxide Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	0.8	4	8	42	83	417	834	
Storage and Feed Tanks	3.90%	3.90%	5.59%	28.12%	39.01%	36.78%	44.54%	23.12%
Heating and Insulation	0.00%	0.00%	0.00%	5.80%	7.84%	9.81%	10.40%	4.84%
Mixer	0.00%	0.00%	0.00%	5.22%	4.59%	6.40%	4.11%	2.90%
Stairway	0.00%	0.00%	0.00%	0.00%	0.00%	3.10%	3.85%	0.99%
Man. Transfer Pump	6.49%	6.49%	6.21%	0.00%	0.00%	0.00%	0.00%	2.74%
Pipes and Valves	20.13%	20.13%	19.25%	13.62%	8.99%	5.48%	5.07%	13.24%
Metering Pump	25.32%	25.32%	24.22%	11.30%	7.84%	11.26%	7.06%	16.05%
Containment Wall	7.79%	7.79%	9.32%	7.83%	7.65%	6.20%	5.65%	7.46%
Labor	18.18%	18.18%	17.39%	12.17%	9.18%	6.71%	5.52%	12.48%
Electrical	5.19%	5.19%	4.97%	2.90%	1.91%	1.24%	0.77%	3.17%
Contingencies	12.99%	12.99%	13.04%	13.04%	13.00%	13.02%	13.03%	13.02%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table B14.1 - Base Costs Obtained from the Water Model for Package Ultrafiltration

Cost Component	Membrane Area (ft2)						Capital Cost Category
	30	424	1,431	3,604	7,155	14,310	
Excavation & Sitework	$1,300	$2,400	$4,100	$5,700	$10,200	$14,900	c
Manufactured Equipment	$5,500	$25,300	$65,600	$129,800	$23,900	$415,100	p
Concrete	$1,800	$3,700	$5,800	$10,200	$16,700	$28,800	p
Labor	$1,100	$5,200	$13,500	$26,900	$49,500	$85,900	c
Pipes and Valves	$500	$1,100	$2,200	$3,800	$4,500	$6,200	p
Electrical	$1,500	$5,600	$13,300	$25,800	$48,100	$85,300	p
Housing	$7,800	$14,600	$21,700	$29,000	$40,800	$56,000	p
Subtotal	$19,500	$57,900	$126,200	$231,200	$193,700	$692,200	
Contingencies	$2,900	$8,700	$18,900	$34,700	$29,100	$103,800	c
Total	$22,400	$66,600	$145,100	$265,900	$222,800	$796,000	

Table B14.2 - Water Model Base Construction Cost Analysis for Package Ultrafiltration

Cost Component	Membrane Area (ft2)						Average Percent
	30	424	1,431	3,604	7,155	14,310	
Excavation & Sitework	5.80%	3.60%	2.83%	2.14%	4.58%	1.87%	3.47%
Manufactured Equipment	24.55%	37.99%	45.21%	48.82%	10.73%	52.15%	36.57%
Concrete	8.04%	5.56%	4.00%	3.84%	7.50%	3.62%	5.42%
Labor	4.91%	7.81%	9.30%	10.12%	22.22%	10.79%	10.86%
Pipes and Valves	2.23%	1.65%	1.52%	1.43%	2.02%	0.78%	1.60%
Electrical	6.70%	8.41%	9.17%	9.70%	21.59%	10.72%	11.05%
Housing	34.82%	21.92%	14.96%	10.91%	18.31%	7.04%	17.99%
Contingencies	12.95%	13.06%	13.03%	13.05%	13.06%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

APPENDIX C

W/W COST MODEL
CAPITAL COST BREAKDOWN SUMMARIES

Table C1.1 - Base Costs Obtained from the WATERCO$T Model for Activated Alumina

Cost Component	Plant Capacity (mgd)						Capital Cost Category
	0.7	2.0	6.8	27	54	135	
Manufactured Equipment	$26,760	$44,580	$138,330	$522,210	$1,031,270	$2,564,560	p
Activated Alumina	$8,300	$14,770	$83,080	$332,310	$664,610	$1,661,530	p
Labor	$10,280	$13,490	$48,010	$192,020	$384,060	$1,282,370	c
Pipes and Valves	$16,260	$19,320	$69,030	$273,210	$542,650	$1,368,060	p
Electrical	$10,050	$11,360	$22,300	$60,300	$119,030	$284,750	p
Housing	$6,960	$27,630	$62,120	$210,980	$374,840	$744,320	p
Contingencies	$11,790	$19,670	$63,430	$238,650	$467,470	$1,185,840	c
Total	$90,400	$150,820	$486,300	$1,829,680	$3,583,930	$9,091,430	

Table C1.2 - WATERCO$T Model Base Construction Cost Analysis for Activated Alumina

Cost Component	Plant Capacity (mgd)						Average Percent
	0.7	2.0	6.8	27	54	135	
Manufactured Equipment	29.60%	29.56%	28.45%	28.54%	28.77%	28.21%	28.86%
Activated Alumina	9.18%	9.79%	17.08%	18.16%	18.54%	18.28%	15.17%
Labor	11.37%	8.94%	9.87%	10.49%	10.72%	14.11%	10.92%
Pipes and Valves	17.99%	12.81%	14.19%	14.93%	15.14%	15.05%	15.02%
Electrical	11.12%	7.53%	4.59%	3.30%	3.32%	3.13%	5.50%
Housing	7.70%	18.32%	12.77%	11.53%	10.46%	8.19%	11.49%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C2.1 - Base Costs Obtained from the WATERCO$T Model for Ammonia Feed Systems

Cost Component	Feed Capacity (lb/day)					Capital Cost Category
	250	500	1,000	2,500	5,000	
Manufactured Equipment	$13,260	$19,520	$30,450	$38,830	$59,200	p
Labor	$3,990	$5,680	$9,250	$10,620	$13,870	c
Pipes and Valves	$2,390	$3,520	$5,500	$7,000	$10,670	p
Electrical	$3,250	$3,770	$6,180	$8,480	$10,990	p
Housing	$4,500	$4,500	$4,500	$4,500	$6,430	p
Contingencies	$4,110	$5,550	$8,380	$10,410	$15,170	c
Total	$31,500	$42,540	$64,260	$79,840	$116,330	

Table C2.2 - WATERCO$T Model Base Construction Cost Analysis for Ammonia Feed Systems

Cost Component	Feed Capacity (lb/day)					Average Percent
	250	500	1,000	2,500	5,000	
Manufactured Equipment	42.10%	45.89%	47.39%	48.63%	50.89%	46.98%
Labor	12.67%	13.35%	14.39%	13.30%	11.92%	13.13%
Pipes and Valves	7.59%	8.27%	8.56%	8.77%	9.17%	8.47%
Electrical	10.32%	8.86%	9.62%	10.62%	9.45%	9.77%
Housing	14.29%	10.58%	7.00%	5.64%	5.53%	8.61%
Contingencies	13.05%	13.05%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C3.1 - Base Costs Obtained from the WATERCO$T Model for Backwash Water Pumping

Cost Component	Pumping Capacity (mgd(gpm))					Capital Cost Category
	1,260 (1.8)	3,150 (4.5)	6,300 (9.1)	18,000 (25.9)	22,950 (33)	
Manufactured Equipment	$11,400	$14,600	$38,380	$76,780	$95,970	p
Labor	$3,050	$4,410	$4,880	$9,290	$12,440	c
Pipes and Valves	$9,780	$17,690	$17,690	$33,390	$44,780	p
Electrical	$13,350	$16,040	$16,740	$28,070	$33,250	p
Contingencies	$5,640	$7,910	$11,650	$22,130	$27,970	c
Total	$43,220	$60,650	$89,340	$169,660	$214,410	

Table C3.2 - WATERCO$T Model Base Construction Cost Analysis for Backwash Water Pumping

Cost Component	Pumping Capacity (mgd(gpm))					Average Percent
	1,260 (1.8)	3,150 (4.5)	6,300 (9.1)	18,000 (25.9)	22,950 (33)	
Manufactured Equipment	26.38%	24.07%	42.96%	45.26%	44.76%	36.68%
Labor	7.06%	7.27%	5.46%	5.48%	5.80%	6.21%
Pipes and Valves	22.63%	29.17%	19.80%	19.68%	20.89%	22.43%
Electrical	30.89%	26.45%	18.74%	16.54%	15.51%	21.63%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.05%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C4.1 - Base Costs Obtained from the WATERCO$T Model for Chemical Sludge Pumping

Cost Component	Capacity (gpm)						Capital Cost Category
	20	100	500	1,000	5,000	10,000	
Excavation & Sitework	$470	$600	$810	$970	$1,840	$2,220	c
Manufactured Equipment	$4,370	$6,230	$8,210	$10,390	$23,320	$38,440	p
Concrete	$1,500	$2,210	$3,220	$4,100	$9,270	$12,310	p
Steel	$1,510	$2,130	$3,120	$3,940	$8,640	$11,070	p
Labor	$5,280	$8,060	$12,880	$17,400	$47,850	$64,720	c
Pipes and Valves	$2,560	$4,570	$10,870	$18,190	$42,810	$79,060	p
Electrical	$6,290	$7,390	$7,880	$9,380	$10,380	$12,510	p
Housing	$5,880	$5,880	$5,880	$8,100	$8,100	$11,700	p
Contingencies	$4,180	$5,560	$7,930	$10,870	$22,830	$34,800	c
Total	$32,040	$42,630	$60,800	$83,340	$175,040	$266,830	

Table C4.2 - WATERCO$T Model Base Construction Cost Analysis for Chemical Sludge Pumping

Cost Component	Capacity (gpm)						
	20	100	500	1,000	5,000	10,000	Average Percent
Excavation & Sitework	1.47%	1.41%	1.33%	1.16%	1.05%	0.83%	1.21%
Manufactured Equipment	13.64%	14.61%	13.50%	12.47%	13.32%	14.41%	13.66%
Concrete	4.68%	5.18%	5.30%	4.92%	5.30%	4.61%	5.00%
Steel	4.71%	5.00%	5.13%	4.73%	4.94%	4.15%	4.78%
Labor	16.48%	18.91%	21.18%	20.88%	27.34%	24.26%	21.51%
Pipes and Valves	7.99%	10.72%	17.88%	21.83%	24.46%	29.63%	18.75%
Electrical	19.63%	17.34%	12.96%	11.26%	5.93%	4.69%	11.97%
Housing	18.35%	13.79%	9.67%	9.72%	4.63%	4.38%	10.09%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C5.1 - Base Costs Obtained from the WATERCO$T Model for Chlorination

Cost Component	Chlorine Feed Capacity (lb/day)						Capital Cost Category
	10	500	1,000	2,000	5,000	10,000	
Manufactured Equipment	$6,760	$21,630	$41,630	$65,950	$76,780	$114,360	p
Labor	$820	$2,610	$5,030	$7,960	$9,270	$13,810	c
Pipes and Valves	$540	$1,710	$3,300	$5,230	$6,080	$9,060	p
Electrical	$770	$2,450	$4,710	$7,460	$8,690	$12,940	p
Housing	$2,430	$18,360	$27,760	$46,550	$100,440	$186,490	p
Contingencies	$1,700	$7,010	$12,360	$19,970	$30,190	$50,500	c
Total	$13,020	$53,770	$94,790	$153,120	$231,450	$387,160	

Table C5.2 - WATERCO$T Model Base Construction Cost Analysis for Chlorination

Cost Component	Chlorine Feed Capacity (lb/day)						Average Percent
	10	500	1,000	2,000	5,000	10,000	
Manufactured Equipment	51.92%	40.23%	43.92%	43.07%	33.17%	29.54%	40.31%
Labor	6.30%	4.85%	5.31%	5.20%	4.01%	3.57%	4.87%
Pipes and Valves	4.15%	3.18%	3.48%	3.42%	2.63%	2.34%	3.20%
Electrical	5.91%	4.56%	4.97%	4.87%	3.75%	3.34%	4.57%
Housing	18.66%	34.15%	29.29%	30.40%	43.40%	48.17%	34.01%
Contingencies	13.06%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C6.1 - Base Costs Obtained from the WATERCO$T Model for Circular Clarifiers

Cost Component	Surface Area (SA=ft2) and Diameter (D=ft)							Capital Cost Category
	SA=707 D=30	SA=1,590 D=45	SA=5,027 D=80	SA=10,387 D=115	SA=15,393 D=140	SA=22,698 D=170	SA=31,416 D=200	
Excavation & Sitework	$1,530	$2,430	$4,900	$7,860	$10,280	$13,520	$17,130	c
Manufactured Equipment	$28,740	$34,410	$69,580	$97,180	$132,350	$189,060	$226,980	p
Concrete	$4,860	$7,710	$15,480	$24,800	$32,400	$42,560	$53,860	p
Steel	$14,160	$21,090	$67,240	$129,250	$188,720	$249,570	$335,140	p
Labor	$10,770	$16,180	$30,960	$46,980	$60,110	$77,640	$96,320	c
Pipes and Valves	$8,090	$8,420	$11,540	$15,660	$21,590	$26,590	$42,520	p
Electrical	$5,940	$5,940	$7,560	$8,270	$10,870	$12,370	$13,060	p
Contingencies	$11,110	$14,430	$31,090	$49,500	$68,450	$91,700	$117,750	c
Total	$85,200	$110,610	$238,350	$379,500	$524,770	$703,010	$902,760	

Table C6.2 - WATERCO$T Model Base Construction Cost Analysis for Circular Clarifiers

Cost Component	Surface Area (SA=ft2) and Diameter (D=ft)							Average Percent
	SA=707 D=30	SA=1,590 D=45	SA=5,027 D=80	SA=10,387 D=115	SA=15,393 D=140	SA=22,698 D=170	SA=31,416 D=200	
Excavation & Sitework	1.80%	2.20%	2.06%	2.07%	1.96%	1.92%	1.90%	1.99%
Manufactured Equipment	33.73%	31.11%	29.19%	25.61%	25.22%	26.89%	25.14%	28.13%
Concrete	5.70%	6.97%	6.49%	6.53%	6.17%	6.05%	5.97%	6.27%
Steel	16.62%	19.07%	28.21%	34.06%	35.96%	35.50%	37.12%	29.51%
Labor	12.64%	14.63%	12.99%	12.38%	11.45%	11.04%	10.67%	12.26%
Pipes and Valves	9.50%	7.61%	4.84%	4.13%	4.11%	3.78%	4.71%	5.53%
Electrical	6.97%	5.37%	3.17%	2.18%	2.07%	1.76%	1.45%	3.28%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C7.1 - Base Costs Obtained from the WATERCO$T Model for Clearwell Storage

Cost Component	Capacity (gal)						Capital Cost Category
	10,000	50,000	100,000	500,000	1,000,000	7,500,000	
Excavation & Sitework	$140	$190	$410	$2,030	$19,440	$30,020	c
Concrete	$8,250	$14,430	$23,280	$66,330	$105,520	$622,500	p
Steel	$5,700	$9,240	$14,550	$32,670	$113,050	$350,700	p
Labor	$13,050	$21,480	$35,040	$84,090	$109,290	$394,160	p
Electrical	$1,270	$1,270	$6,010	$6,010	$9,800	$9,800	p
Contingencies	$4,260	$6,990	$11,890	$28,670	$53,570	$211,080	c
Total	$32,670	$53,600	$91,180	$219,800	$410,670	$1,618,260	

Table C7.2 - WATERCO$T Model Base Construction Cost Analysis for Clearwell Storage

Cost Component	Capacity (gal)						Average Percent
	10,000	50,000	100,000	500,000	1,000,000	7,500,000	
Excavation & Sitework	0.43%	0.35%	0.45%	0.92%	4.73%	1.86%	1.46%
Concrete	25.25%	26.92%	25.53%	30.18%	25.69%	38.47%	28.67%
Steel	17.45%	17.24%	15.96%	14.86%	27.53%	21.67%	19.12%
Labor	39.94%	40.07%	38.43%	38.26%	26.61%	24.36%	34.61%
Electrical	3.89%	2.37%	6.59%	2.73%	2.39%	0.61%	3.10%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C8.1 - Base Costs Obtained from the WATERCO$T Model for Ferric Chloride Feed Systems*

Cost Component	Feed Capacity (lb/hr) 10.7	107	1,070	5,350	Capital Cost Category
Manufactured Equipment	$7,500	$13,100	$33,560	$160,940	p
Labor	$420	$1,130	$2,430	$12,160	c
Pipes and Valves	$2,000	$2,500	$3,000	$15,000	p
Electrical	$1,110	$2,260	$4,960	$19,000	p
Housing	$6,000	$13,300	$51,270	$174,590	p
Contingencies	$2,550	$4,840	$14,280	$57,250	c
Total	$19,580	$37,130	$109,500	$438,940	

*Numbers were unavailable for ferric chloride. However, numbers presented for ferrous sulfate and ferricsulfate were identical. It was assumed that these same relationships apply to ferric chloride

Table C8.2 - WATERCO$T Model Base Construction Cost Analysis for Ferric Chloride Feed Systems*

Cost Component	Feed Capacity (lb/hr) 10.7	107	1,070	5,350	Average Percent
Manufactured Equipment	38.30%	35.28%	30.65%	36.67%	35.22%
Labor	2.15%	3.04%	2.22%	2.77%	2.54%
Pipes and Valves	10.21%	6.73%	2.74%	3.42%	5.78%
Electrical	5.67%	6.09%	4.53%	4.33%	5.15%
Housing	30.64%	35.82%	46.82%	39.78%	38.27%
Contingencies	13.02%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

*Numbers were unavailable for ferric chloride. However, numbers presented for ferrous sulfate and ferricsulfate were identical. It was assumed that these same relationships apply to ferric chloride

Table C9.1 - Base Costs Obtained from the WATERCOST Model for Finished Water Pumping

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.5	15	150	300	
Manufactured Equipment	$15,410	$89,700	$567,600	$1,142,350	p
Labor	$3,880	$11,580	$80,400	$158,840	c
Pipes and Valves	$5,200	$16,570	$139,200	$270,100	p
Electrical	$7,180	$38,450	$210,490	$400,230	p
Contingencies	$4,750	$23,450	$149,650	$295,730	c
Total	$36,420	$179,750	$1,147,340	$2,267,250	

Table C9.2 - WATERCOST Model Base Construction Cost Analysis for Finished Water Pumping

Cost Component	Plant Capacity (mgd)				Average Percent
	1.5	15	150	300	
Manufactured Equipment	42.31%	49.90%	49.47%	50.38%	48.02%
Labor	10.65%	6.44%	7.01%	7.01%	7.78%
Pipes and Valves	14.28%	9.22%	12.13%	11.91%	11.89%
Electrical	19.71%	21.39%	18.35%	17.65%	19.28%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C10.1 - Base Costs Obtained from the WATERCO$T Model for Gravity Filtration

Cost Component	Total Filter Area (FA-ft2) and Plant Flow (Q=mgd) FA=140 Q=1	FA=700 Q=5	FA=1,400 Q=10	FA=7,000 Q=50	FA=14,000 Q=100	FA=28,000 Q=200	Capital Cost Category
Excavation & Sitework	$1,950	$3,620	$5,520	$16,220	$25,590	$43,410	c
Manufactured Equipment	$26,360	$56,960	$78,300	$305,170	$529,360	$982,390	p
Concrete	$13,400	$27,040	$41,660	$95,490	$154,790	$275,570	p
Steel	$11,550	$19,960	$30,120	$73,530	$123,160	$209,960	p
Labor	$40,580	$88,490	$150,870	$356,380	$508,980	$1,000,670	c
Pipes and Valves	$20,580	$79,020	$127,340	$420,670	$590,150	$1,125,500	p
Electrical	$13,390	$38,410	$38,410	$99,140	$168,840	$265,310	p
Housing	$17,400	$40,480	$70,590	$291,940	$514,330	$968,520	p
Contingencies	$21,780	$53,100	$81,420	$248,780	$392,280	$730,700	c
Total	$166,990	$407,080	$624,230	$1,907,320	$3,007,480	$5,602,030	

Table C10.2 - WATERCO$T Model Base Construction Cost Analysis for Gravity Filtration

Cost Component	Total Filter Area (FA-ft2) and Plant Flow (Q=mgd) FA=140 Q=1	FA=700 Q=5	FA=1,400 Q=10	FA=7,000 Q=50	FA=14,000 Q=100	FA=28,000 Q=200	Average Percent
Excavation & Sitework	1.17%	0.89%	0.88%	0.85%	0.85%	0.77%	0.90%
Manufactured Equipment	15.79%	13.99%	12.54%	16.00%	17.60%	17.54%	15.58%
Concrete	8.02%	6.64%	6.67%	5.01%	5.15%	4.92%	6.07%
Steel	6.92%	4.90%	4.83%	3.86%	4.10%	3.75%	4.72%
Labor	24.30%	21.74%	24.17%	18.68%	16.92%	17.86%	20.61%
Pipes and Valves	12.32%	19.41%	20.40%	22.06%	19.62%	20.09%	18.98%
Electrical	8.02%	9.44%	6.15%	5.20%	5.61%	4.74%	6.53%
Housing	10.42%	9.94%	11.31%	15.31%	17.10%	17.29%	13.56%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C11.1 - Base Costs Obtained from the WATERCO$T Model for Horizontal Paddle, G=50

Cost Component	Total Basin Volume (ft3)						Capital Cost Category
	1,800	10,000	25,000	100,000	500,000	1,000,000	
Excavation & Sitework	$470	$2,550	$4,290	$9,970	$40,080	$77,640	p
Manufactured Equipment	$12,140	$28,250	$35,410	$74,400	$220,800	$433,640	p
Concrete	$1,400	$7,610	$12,740	$29,770	$120,280	$232,960	p
Steel	$2,360	$12,550	$20,440	$46,500	$175,290	$339,510	p
Labor	$7,080	$20,220	$29,420	$75,460	$221,200	$439,770	c
Electrical	$6,980	$28,320	$28,320	$28,320	$141,610	$283,220	p
Contingencies	$4,560	$14,930	$19,590	$39,660	$137,890	$271,010	c
Total	$34,990	$114,430	$150,210	$304,080	$1,057,150	$2,077,750	

Table C11.2 - WATERCO$T Model Base Construction Cost Analysis for Horizontal Paddle, G=50

Cost Component	Total Basin Volume (ft3)						Average Percent
	1,800	10,000	25,000	100,000	500,000	1,000,000	
Excavation & Sitework	1.34%	2.23%	2.86%	3.28%	3.79%	3.74%	2.87%
Manufactured Equipment	34.70%	24.69%	23.57%	24.47%	20.89%	20.87%	24.86%
Concrete	4.00%	6.65%	8.48%	9.79%	11.38%	11.21%	8.59%
Steel	6.74%	10.97%	13.61%	15.29%	16.58%	16.34%	13.26%
Labor	20.23%	17.67%	19.59%	24.82%	20.92%	21.17%	20.73%
Electrical	19.95%	24.75%	18.85%	9.31%	13.40%	13.63%	16.65%
Contingencies	13.03%	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C12.1 - Base Costs Obtained from the WATERCO$T Model for Horizontal Paddle, G=80

Cost Component	Total Basin Volume (ft3)					Capital Cost Category
	1,800	10,000	25,000	100,000	500,000	
Excavation & Sitework	$470	$2,550	$4,290	$9,970	$40,080	c
Manufactured Equipment	$12,140	$34,210	$44,360	$115,770	$427,670	p
Concrete	$1,400	$7,610	$12,740	$29,770	$120,280	p
Steel	$2,360	$12,550	$20,440	$46,500	$175,290	p
Labor	$7,080	$22,190	$32,370	$90,170	$289,520	p
Electrical	$6,980	$28,320	$28,320	$28,320	$141,610	p
Contingencies	$4,560	$16,110	$21,380	$48,080	$179,170	c
Total	$34,990	$123,540	$163,900	$368,580	$1,373,620	

Table C12.2 - WATERCO$T Model Base Construction Cost Analysis for Horizontal Paddle, G=80

Cost Component	Total Basin Volume (ft3)					Average Percent
	1,800	10,000	25,000	100,000	500,000	
Excavation & Sitework	1.34%	2.06%	2.62%	2.70%	2.92%	2.33%
Manufactured Equipment	34.70%	27.69%	27.07%	31.41%	31.13%	30.40%
Concrete	4.00%	6.16%	7.77%	8.08%	8.76%	6.95%
Steel	6.74%	10.16%	12.47%	12.62%	12.76%	10.95%
Labor	20.23%	17.96%	19.75%	24.46%	21.08%	20.70%
Electrical	19.95%	22.92%	17.28%	7.68%	10.31%	15.63%
Contingencies	13.03%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C13.1 - Base Costs Obtained from the WATERCO$T Model for Hydraulic Surface Wash

Cost Component	Total Filter Area (ft2)						Capital Cost Category
	140	700	1,400	7,000	14,000	28,000	
Manufactured Equipment	$9,170	$12,050	$35,090	$82,010	$172,440	$401,200	p
Labor	$1,300	$2,770	$5,170	$14,710	$29,430	$66,600	c
Pipes and Valves	$2,570	$5,100	$7,020	$13,390	$32,290	$59,870	p
Electrical	$12,670	$17,920	$20,440	$37,900	$61,120	$92,360	p
Contingencies	$3,860	$5,680	$10,160	$22,200	$44,290	$93,000	c
Total	$29,570	$43,520	$77,880	$170,210	$339,570	$713,030	

Table C13.2 - WATERCO$T Model Base Construction Cost Analysis for Hydraulic Surface Wash

Cost Component	Total Filter Area (ft2)						Average Percent
	140	700	1,400	7,000	14,000	28,000	
Manufactured Equipment	31.01%	27.69%	45.06%	48.18%	50.78%	56.27%	43.16%
Labor	4.40%	6.36%	6.64%	8.64%	8.67%	9.34%	7.34%
Pipes and Valves	8.69%	11.72%	9.01%	7.87%	9.51%	8.40%	9.20%
Electrical	42.85%	41.18%	26.25%	22.27%	18.00%	12.95%	27.25%
Contingencies	13.05%	13.05%	13.05%	13.04%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C14.1 - Base Costs Obtained from the WATERCO$T Model for In-Plant Pumping

Cost Component	Pumping Capacity (mgd)						Capital Cost Category
	1	5	10	50	100	200	
Excavation & Sitework	$100	$100	$130	$360	$600	$1,030	c
Manufactured Equipment	$6,300	$9,110	$14,780	$48,650	$83,400	$152,900	p
Concrete	$970	$970	$1,510	$4,770	$8,030	$14,090	p
Steel	$1,610	$1,610	$2,450	$7,630	$12,500	$21,330	p
Labor	$5,570	$10,410	$24,070	$63,330	$129,130	$331,030	c
Pipes and Valves	$5,090	$12,330	$16,300	$60,230	$114,200	$222,080	p
Electrical	$3,170	$4,930	$7,390	$25,760	$47,240	$89,360	p
Housing	$1,500	$1,500	$3,000	$14,520	$28,830	$58,080	p
Contingencies	$3,650	$6,140	$10,440	$33,790	$63,590	$133,490	c
Total	$27,960	$47,100	$80,070	$259,040	$487,520	$1,023,390	

Table C14.2 - WATERCO$T Model Base Construction Cost Analysis for In-Plant Pumping

Cost Component	Pumping Capacity (mgd)						Average Percent
	1	5	10	50	100	200	
Excavation & Sitework	0.36%	0.21%	0.16%	0.14%	0.12%	0.10%	0.18%
Manufactured Equipment	22.53%	19.34%	18.46%	18.78%	17.11%	14.94%	18.53%
Concrete	3.47%	2.06%	1.89%	1.84%	1.65%	1.38%	2.05%
Steel	5.76%	3.42%	3.06%	2.95%	2.56%	2.08%	3.31%
Labor	19.92%	22.10%	30.06%	24.45%	26.49%	32.35%	25.89%
Pipes and Valves	18.20%	26.18%	20.36%	23.25%	23.42%	21.70%	22.19%
Electrical	11.34%	10.47%	9.23%	9.94%	9.69%	8.73%	9.90%
Housing	5.36%	3.18%	3.75%	5.61%	5.91%	5.68%	4.92%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C15.1 - Base Costs Obtained from the WATERCO$T Model for Ion Exchange

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.1	3.7	6.1	12.3	
Excavation & Sitework	$740	$1,140	$1,470	$1,970	c
Manufactured Equipment	$39,960	$89,580	$137,770	$258,230	p
Media	$92,790	$313,160	$521,940	$1,043,880	p
Concrete	$2,410	$3,580	$4,750	$6,320	p
Steel	$3,830	$5,680	$7,530	$9,950	p
Labor	$17,420	$33,510	$61,460	$125,080	c
Pipes and Valves	$14,040	$38,780	$69,740	$139,480	p
Electrical	$27,700	$38,510	$60,820	$120,210	p
Housing	$21,920	$35,660	$57,440	$79,820	p
Contingencies	$33,120	$83,940	$138,440	$267,740	c
Total	$253,930	$643,540	$1,061,360	$2,052,680	

Table C15.2 - WATERCO$T Model Base Construction Cost Analysis for Ion Exchange

Cost Component	Plant Capacity (mgd)				Average Percent
	1.1	3.7	6.1	12.3	
Excavation & Sitework	0.29%	0.18%	0.14%	0.10%	0.18%
Manufactured Equipment	15.74%	13.92%	12.98%	12.58%	13.80%
Media	36.54%	48.66%	49.18%	50.85%	46.31%
Concrete	0.95%	0.56%	0.45%	0.31%	0.57%
Steel	1.51%	0.88%	0.71%	0.48%	0.90%
Labor	6.86%	5.21%	5.79%	6.09%	5.99%
Pipes and Valves	5.53%	6.03%	6.57%	6.80%	6.23%
Electrical	10.91%	5.98%	5.73%	5.86%	7.12%
Housing	8.63%	5.54%	5.41%	3.89%	5.87%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C16.1 - Base Costs Obtained from the WATERCO$T Model for Lime Feed with Recalcination

Cost Component	Feed Capacity (lb/hr) 1,000	10,000	Capital Cost Category
Manufactured Equipment	$48,870	$80,660	p
Labor	$1,510	$3,060	c
Pipes and Valves	$3,120	$6,250	p
Electrical	$6,880	$12,320	p
Housing	$9,450	$26,250	p
Contingencies	$10,470	$19,280	c
Total	$80,300	$147,820	

Table C16.2 - WATERCO$T Model Base Construction Cost Analysis for Lime Feed with Recalcination

Cost Component	Feed Capacity (lb/hr) 1,000	10,000	Average Percent
Manufactured Equipment	60.86%	54.57%	57.71%
Labor	1.88%	2.07%	1.98%
Pipes and Valves	3.89%	4.23%	4.06%
Electrical	8.57%	8.33%	8.45%
Housing	11.77%	17.76%	14.76%
Contingencies	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%

Table C17.1 - Base Costs Obtained from the WATERCO$T Model for Permanganate Feed Systems

Cost Component	Feed Capacity (lb/day)				Capital Cost Category
	1	10	100	500	
Manufactured Equipment	$2,340	$2,600	$3,380	$5,220	p
Labor	$480	$480	$540	$770	c
Pipes and Valves	$970	$970	$970	$970	p
Electrical	$3,190	$3,190	$3,190	$3,190	p
Housing	$1,260	$1,580	$1,950	$2,940	p
Contingencies	$1,240	$1,320	$1,500	$1,960	c
Total	$9,480	$10,140	$11,530	$15,050	

Table C17.2 - WATERCO$T Model Base Construction Cost Analysis for Permanganate Feed Systems

Cost Component	Feed Capacity (lb/day)				
	1	10	100	500	Average Percent
Manufactured Equipment	24.68%	25.64%	29.31%	34.68%	28.58%
Labor	5.06%	4.73%	4.68%	5.12%	4.90%
Pipes and Valves	10.23%	9.57%	8.41%	6.45%	8.66%
Electrical	33.65%	31.46%	27.67%	21.20%	28.49%
Housing	13.29%	15.58%	16.91%	19.53%	16.33%
Contingencies	13.08%	13.02%	13.01%	13.02%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C18.1 - Base Costs Obtained from the WATERCO$T Model for Polymer Feed Systems

Cost Component	Feed Capacity (lb/hr)				Capital Cost Category
	1	10	100	200	
Manufactured Equipment	$11,670	$11,670	$14,730	$18,970	p
Labor	$700	$700	$700	$760	c
Pipes and Valves	$280	$280	$280	$300	p
Electrical	$1,290	$1,290	$1,290	$1,290	p
Housing	$3,600	$3,600	$4,050	$4,500	p
Contingencies	$2,630	$2,630	$3,160	$3,870	c
Total	$20,170	$20,170	$24,210	$29,690	

Table C18.2 - WATERCO$T Model Base Construction Cost Analysis for Polymer Feed Systems

Cost Component	Feed Capacity (lb/hr)				
	1	10	100	200	Average Percent
Manufactured Equipment	57.86%	57.86%	60.84%	63.89%	60.11%
Labor	3.47%	3.47%	2.89%	2.56%	3.10%
Pipes and Valves	1.39%	1.39%	1.16%	1.01%	1.24%
Electrical	6.40%	6.40%	5.33%	4.34%	5.62%
Housing	17.85%	17.85%	16.73%	15.16%	16.90%
Contingencies	13.04%	13.04%	13.05%	13.03%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C19.1 - Base Costs Obtained from the WATERCO$T Model for Rapid Mix, G=900

Cost Component	Basin Volume (ft3)						Capital Cost Category
	100	500	1,000	5,000	10,000	20,000	
Excavation & Sitework	$220	$380	$490	$1,360	$2,720	$5,460	c
Manufactured Equipment	$4,310	$9,830	$14,760	$66,840	$133,670	$267,340	p
Concrete	$390	$870	$1,280	$3,610	$7,220	$14,450	p
Steel	$570	$1,350	$2,010	$5,600	$11,180	$22,360	p
Labor	$1,230	$2,300	$3,410	$13,140	$26,280	$52,550	c
Electrical	$6,980	$6,980	$7,180	$7,470	$8,760	$16,100	p
Contingencies	$2,060	$3,260	$4,370	$14,700	$28,470	$56,740	c
Total	$15,760	$24,970	$33,500	$112,720	$218,300	$435,000	

Table C19.2 - WATERCO$T Model Base Construction Cost Analysis for Rapid Mix, G=900

Cost Component	Basin Volume (ft3)						
	100	500	1,000	5,000	10,000	20,000	Average Percent
Excavation & Sitework	1.40%	1.52%	1.46%	1.21%	1.25%	1.26%	1.35%
Manufactured Equipment	27.35%	39.37%	44.06%	59.30%	61.23%	61.46%	48.79%
Concrete	2.47%	3.48%	3.82%	3.20%	3.31%	3.32%	3.27%
Steel	3.62%	5.41%	6.00%	4.97%	5.12%	5.14%	5.04%
Labor	7.80%	9.21%	10.18%	11.66%	12.04%	12.08%	10.50%
Electrical	44.29%	27.95%	21.43%	6.63%	4.01%	3.70%	18.00%
Contingencies	13.07%	13.06%	13.04%	13.04%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C20.1 - Base Costs Obtained from the WATERCOST Model for Recarbonation, Liquid Carbon Dioxide

Cost Component	Installed Capacity (lb/day)						Capital Cost Category
	380	750	1,500	3,750	7,500	15,000	
Manufactured Equipment	$27,000	$31,000	$35,250	$49,250	$73,000	$141,000	p
Labor	$7,650	$8,780	$12,170	$17,330	$28,990	$58,010	c
Pipes and Valves	$1,530	$2,340	$4,620	$8,710	$16,940	$37,540	p
Housing	$7,360	$7,360	$7,360	$7,360	$8,450	$8,900	p
Contingencies	$6,530	$7,420	$8,910	$12,400	$19,110	$36,820	c
Total	$50,070	$56,900	$68,310	$95,050	$146,490	$282,270	

Table C20.2 - WATERCOST Model Base Construction Cost Analysis for Recarbonation, Liquid Carbon Dioxide

Cost Component	Installed Capacity (lb/day)						Average Percent
	380	750	1,500	3,750	7,500	15,000	
Manufactured Equipment	53.92%	54.48%	51.60%	51.81%	49.83%	49.95%	51.93%
Labor	15.28%	15.43%	17.82%	18.23%	19.79%	20.55%	17.85%
Pipes and Valves	3.06%	4.11%	6.76%	9.16%	11.56%	13.30%	7.99%
Housing	14.70%	12.93%	10.77%	7.74%	5.77%	3.15%	9.18%
Contingencies	13.04%	13.04%	13.04%	13.05%	13.05%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C21.1 - Base Costs Obtained from the WATERCO$T Model for Recarbonation Basins

Cost Component	Single Basin Volume (ft3)							Capital Cost Category
	770	1,375	2,750	5,630	8,800	17,600	35,200	
Excavation & Sitework	$520	$620	$980	$1,390	$1,790	$3,050	$5,570	c
Concrete	$1,380	$1,860	$2,820	$4,050	$5,190	$8,570	$15,320	p
Steel	$2,250	$3,010	$4,670	$6,560	$8,320	$13,960	$25,240	p
Labor	$2,830	$3,800	$5,730	$8,090	$10,240	$16,740	$29,730	c
Pipes and Valves	$90	$130	$250	$480	$680	$1,360	$3,360	p
Contingencies	$1,060	$1,410	$2,170	$3,090	$3,930	$6,550	$11,880	c
Total	$8,130	$10,830	$16,620	$23,660	$30,150	$50,230	$91,100	

Table C21.2 - WATERCO$T Model Base Construction Cost Analysis for Recarbonation Basins

Cost Component	Single Basin Volume (ft3)							Average Percent
	770	1,375	2,750	5,630	8,800	17,600	35,200	
Excavation & Sitework	6.40%	5.72%	5.90%	5.87%	5.94%	6.07%	6.11%	6.00%
Concrete	16.97%	17.17%	16.97%	17.12%	17.21%	17.06%	16.82%	17.05%
Steel	27.68%	27.79%	28.10%	27.73%	27.60%	27.79%	27.71%	27.77%
Labor	34.81%	35.09%	34.48%	34.19%	33.96%	33.33%	32.63%	34.07%
Pipes and Valves	1.11%	1.20%	1.50%	2.03%	2.26%	2.71%	3.69%	2.07%
Contingencies	13.04%	13.02%	13.06%	13.06%	13.03%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C22.1 - Base Costs Obtained from the WATERCO$T Model for Rectangular Clarifiers

Cost Component	Area (A=ft2) and Length x Width (LW=ftxft)						Capital Cost Category
	A=240 LW=30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation & Sitework	$1,060	$2,000	$3,060	$4,680	$6,670	$8,090	c
Manufactured Equipment	$8,540	$12,080	$24,470	$32,020	$53,110	$63,440	p
Concrete	$2,970	$5,490	$8,430	$12,820	$18,190	$22,070	p
Steel	$6,400	$13,110	$19,440	$32,620	$51,250	$69,680	p
Labor	$6,220	$11,260	$17,320	$26,390	$37,570	$45,300	c
Pipes and Valves	$6,960	$7,400	$9,100	$12,500	$16,100	$21,450	p
Electrical	$1,510	$1,760	$1,860	$2,020	$2,110	$2,400	p
Contingencies	$5,050	$7,970	$12,550	$18,460	$27,750	$34,860	c
Total	$38,710	$61,070	$96,230	$141,510	$212,750	$267,290	

Table C22.2 - WATERCO$T Model Base Construction Cost Analysis for Rectangular Clarifiers

Cost Component	Area (A=ft2) and Length x Width (LW=ftxft)						Average Percent
	A=240 LW=30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation & Sitework	2.74%	3.27%	3.18%	3.31%	3.14%	3.03%	3.11%
Manufactured Equipment	22.06%	19.78%	25.43%	22.63%	24.96%	23.73%	23.10%
Concrete	7.67%	8.99%	8.76%	9.06%	8.55%	8.26%	8.55%
Steel	16.53%	21.47%	20.20%	23.05%	24.09%	26.07%	21.90%
Labor	16.07%	18.44%	18.00%	18.65%	17.66%	16.95%	17.63%
Pipes and Valves	17.98%	12.12%	9.46%	8.83%	7.57%	8.02%	10.66%
Electrical	3.90%	2.88%	1.93%	1.43%	0.99%	0.90%	2.01%
Contingencies	13.05%	13.05%	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C23.1 - Base Costs Obtained from the WATERCO$T Model for Reverse Osmosis

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.0	10	100	200	
Manufactured Equipment	$474,210	$3,458,480	$29,174,260	$56,438,930	p
Labor	$70,420	$346,850	$2,312,340	$2,837,870	c
Electrical	$65,740	$486,270	$3,635,690	$6,947,480	p
Housing	$64,260	$462,650	$2,409,660	$4,176,740	p
Contingencies	$101,190	$713,140	$5,629,790	$10,560,150	c
Total	$775,820	$5,467,390	$43,161,740	$80,961,170	

Table C23.2 - WATERCO$T Model Base Construction Cost Analysis for Reverse Osmosis

Cost Component	Plant Capacity (mgd)				Average Percent
	1.0	10	100	200	
Manufactured Equipment	61.12%	63.26%	67.59%	69.71%	65.42%
Labor	9.08%	6.34%	5.36%	3.51%	6.07%
Electrical	8.47%	8.89%	8.42%	8.58%	8.59%
Housing	8.28%	8.46%	5.58%	5.16%	6.87%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C24.1 - Base Costs Obtained from the WATERCO$T Model for Sodium Hydroxide Feed Systems

Cost Component	Feed Capacity (lb/day)				Capital Cost Category
	10	100	1,000	10000	
Manufactured Equipment	$6,440	$7,010	$5,720	$19,450	p
Labor	$640	$640	$790	$4,120	c
Pipes and Valves	$850	$850	$850	$850	p
Electrical	$3,190	$3,190	$3,190	$3,460	p
Housing	$1,010	$2,100	$8,400	$48,380	p
Contingencies	$1,820	$2,070	$2,840	$11,440	c
Total	$13,950	$15,860	$21,790	$87,700	

Table C24.2 - WATERCO$T Model Base Construction Cost Analysis for Sodium Hydroxide Feed Systems

Cost Component	Feed Capacity (lb/day)				Average Percent
	10	100	1,000	10,000	
Manufactured Equipment	46.16%	44.20%	26.25%	22.18%	34.70%
Labor	4.59%	4.04%	3.63%	4.70%	4.24%
Pipes and Valves	6.09%	5.36%	3.90%	0.97%	4.08%
Electrical	22.87%	20.11%	14.64%	3.95%	15.39%
Housing	7.24%	13.24%	38.55%	55.17%	28.55%
Contingencies	13.05%	13.05%	13.03%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C25.1 - Base Costs Obtained from the WATERCO$T Model for Sulfuric Acid Feed Systems

Cost Component	Feed Capacity (gpd) 10	100	1000	5000	Capital Cost Category
Manufactured Equipment	$1,560	$3,440	$12,400	$41,000	p
Labor	$640	$820	$2,840	$11,840	c
Pipes and Valves	$1,090	$1,090	$2,150	$2,150	p
Electrical	$1,670	$2,920	$2,920	$2,920	p
Housing	$2,520	$1,560	$1,560	$1,560	p
Contingencies	$1,120	$1,470	$3,280	$8,920	c
Total	$8,600	$11,300	$25,150	$68,390	

Table C25.2 - WATERCO$T Model Base Construction Cost Analysis for Sulfuric Acid Feed Systems

Cost Component	Feed Capacity (gpd) 10	100	1000	5000	Average Percent
Manufactured Equipment	18.14%	30.44%	49.30%	59.95%	39.46%
Labor	7.44%	7.26%	11.29%	17.31%	10.83%
Pipes and Valves	12.67%	9.65%	8.55%	3.14%	8.50%
Electrical	19.42%	25.84%	11.61%	4.27%	15.28%
Housing	29.30%	13.81%	6.20%	2.28%	12.90%
Contingencies	13.02%	13.01%	13.04%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table C26.1 - Base Costs Obtained from the WATERCO$T Model for Tube Settling Modules

Cost Component	Tube Module Area (ft2)					Capital Cost Category
	280	2,800	14,000	28,000	56,000	
Manufactured Equipment	$4,200	$31,000	$147,000	$282,000	$504,000	p
Steel	$2,000	$19,500	$95,000	$155,000	$300,000	p
Labor	$2,500	$11,200	$49,000	$95,000	$224,000	c
Contingencies	$1,300	$9,300	$43,700	$79,800	$154,200	c
Total	$10,000	$71,000	$334,700	$611,800	$1,182,200	

Table C26.2 - WATERCO$T Model Base Construction Cost Analysis for Tube Settling Modules

Cost Component	Tube Module Area (ft2)					Average Percent
	280	2,800	14,000	28,000	56,000	
Manufactured Equipment	42.00%	43.66%	43.92%	46.09%	42.63%	43.66%
Steel	20.00%	27.46%	28.38%	25.34%	25.38%	25.31%
Labor	25.00%	15.77%	14.64%	15.53%	18.95%	17.98%
Contingencies	13.00%	13.10%	13.06%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table C27.1 - Base Costs Obtained from the WATERCO$T Model for Wash Water Surge Basins

Cost Component	Capacity (gal)				Capital Cost Category
	10,000	50,000	100,000	500,000	
Excavation & Sitework	$200	$520	$1,250	$4,400	c
Concrete	$11,560	$39,310	$71,480	$143,680	p
Steel	$7,990	$25,170	$44,680	$70,770	p
Labor	$18,270	$58,500	$107,590	$182,150	c
Pipes and Valves	$5,500	$7,500	$11,000	$16,000	p
Electrical	$1,300	$1,300	$6,000	$6,000	p
Contingencies	$6,720	$19,850	$36,300	$63,450	c
Total	$51,540	$152,150	$278,300	$486,450	

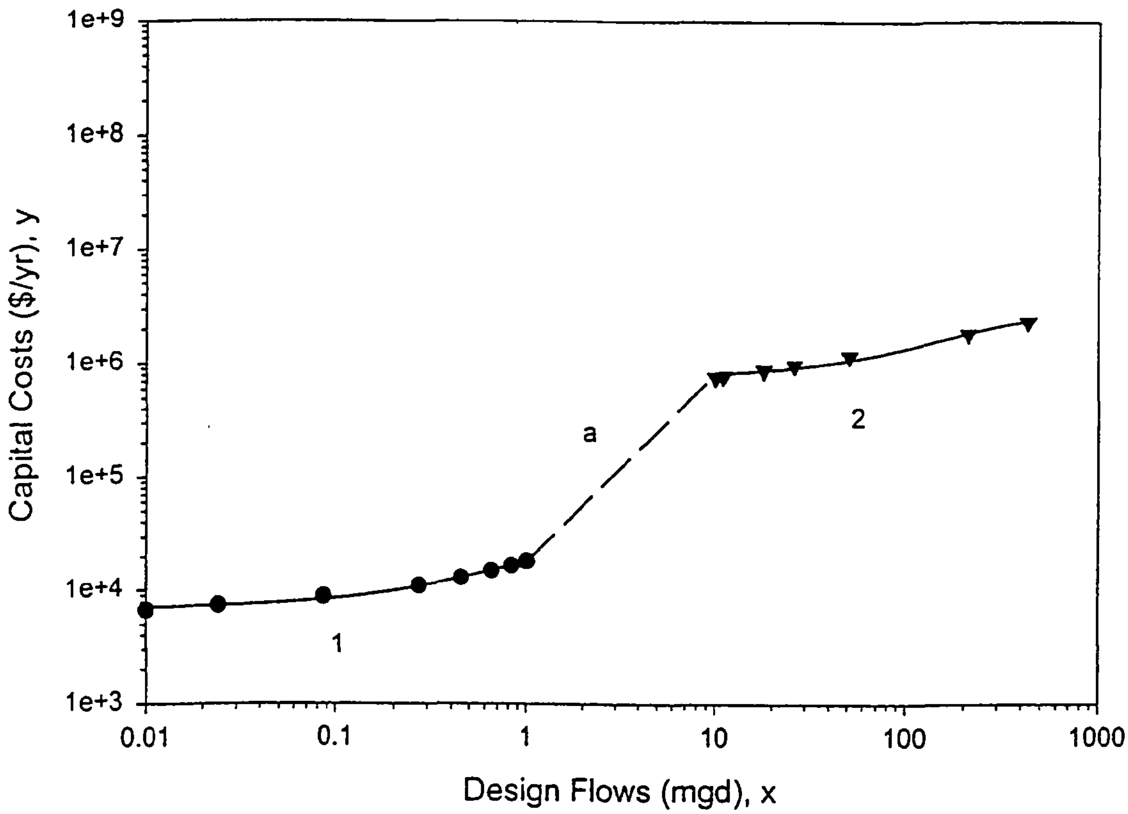
Table C27.2 - WATERCO$T Model Base Construction Cost Analysis for Wash Water Surge Basins

Cost Component	Capacity (gal)				Average Percent
	10,000	50,000	100,000	500,000	
Excavation & Sitework	0.39%	0.34%	0.45%	0.90%	0.52%
Concrete	22.43%	25.84%	25.68%	29.54%	25.87%
Steel	15.50%	16.54%	16.05%	14.55%	15.66%
Labor	35.45%	38.45%	38.66%	37.44%	37.50%
Pipes and Valves	10.67%	4.93%	3.95%	3.29%	5.71%
Electrical	2.52%	0.85%	2.16%	1.23%	1.69%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

APPENDIX D

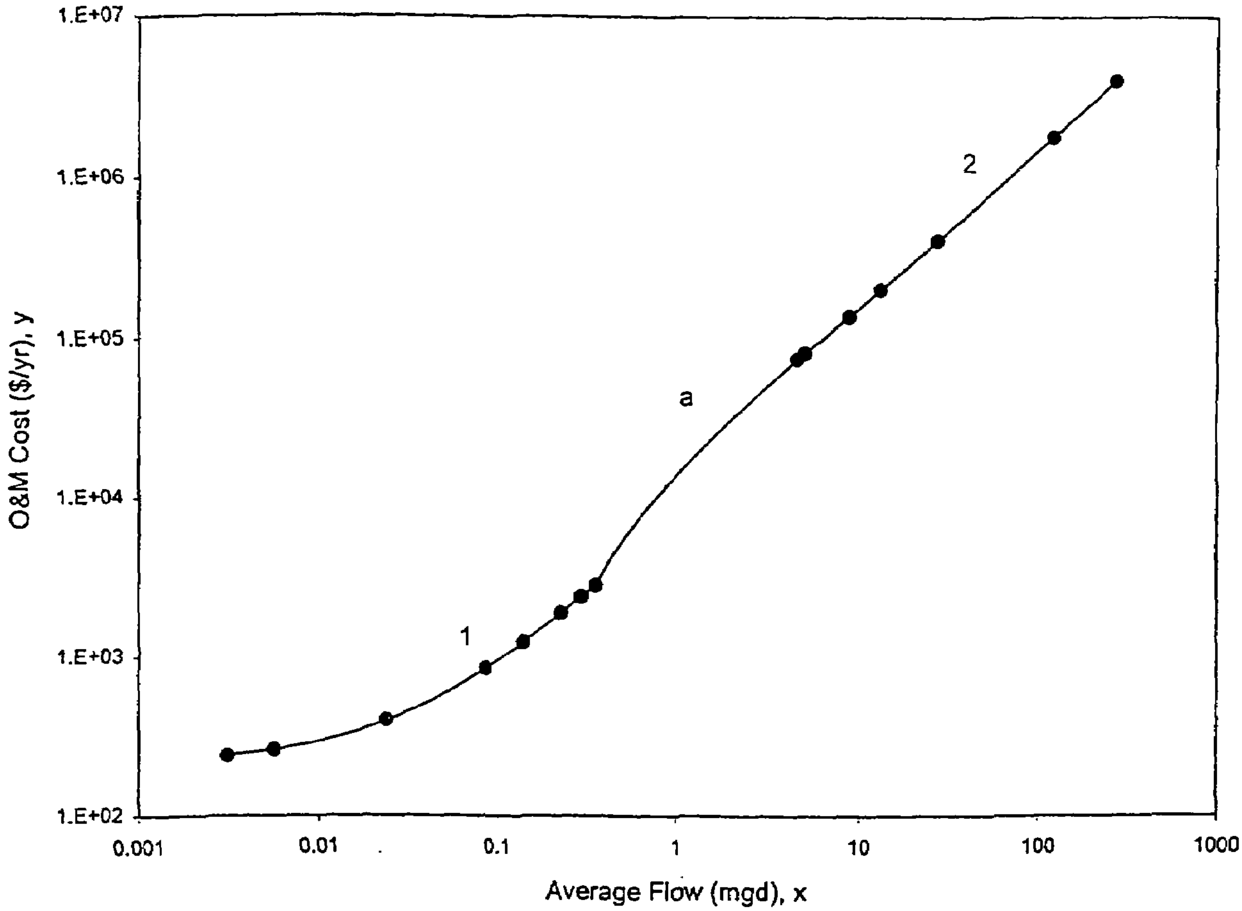
COST EQUATIONS AND CURVE FITS FOR REMOVAL AND ACCESSORY COSTS

Figure D-1
Capital Costs for Enhanced Coagulation/Filtration



Accessories Costs	**Applicable Flow Range**
$y = 0$	0.01 - 430 mgd
Removal Costs	
a. $y = 89662x - 71592$	1 - 10 mgd
1. $y = 7027 + 14922x - 3879x^2$ $R^2 = .99$	0.01 - 1 mgd
2. $y = 756410 + 6937x - 7.55x^2$ $R^2 = .99$	10 - 430 mgd

Figure D-2
O&M Costs for Enhanced Coagulation/Filtration

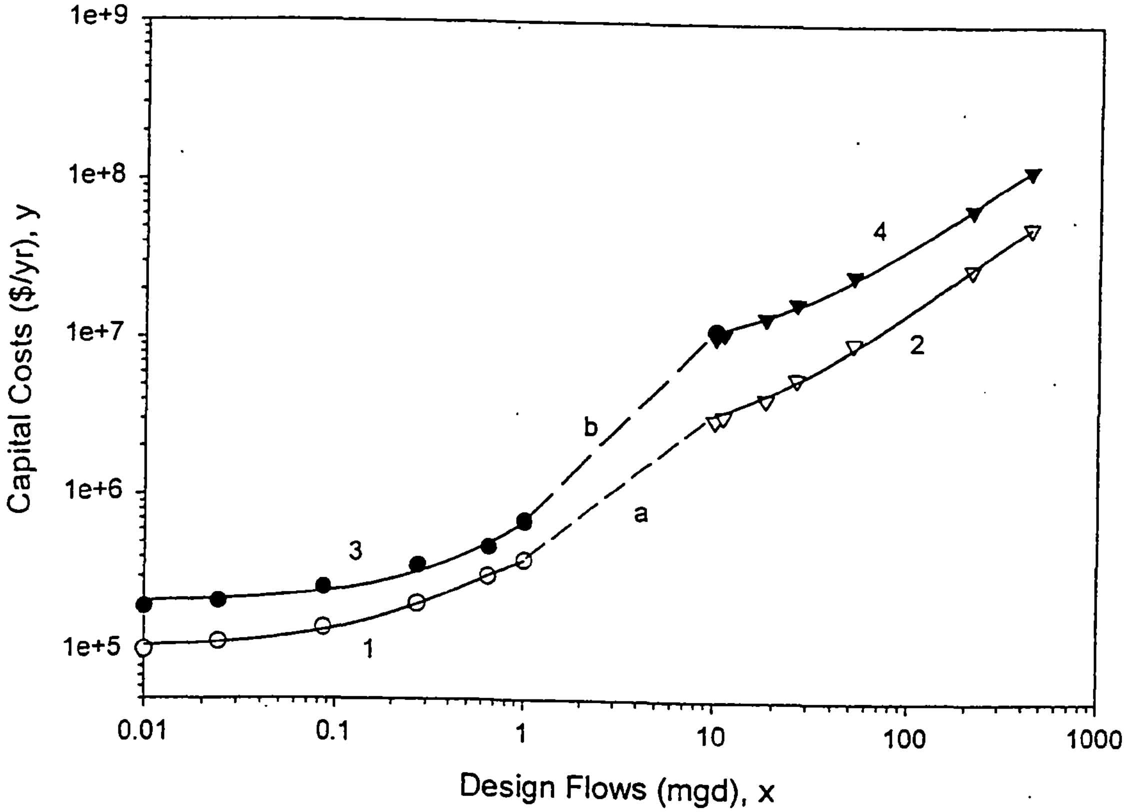


Accessories Costs	Applicable Flow Range
y = 0	0.003 - 270 mgd

Removal Costs

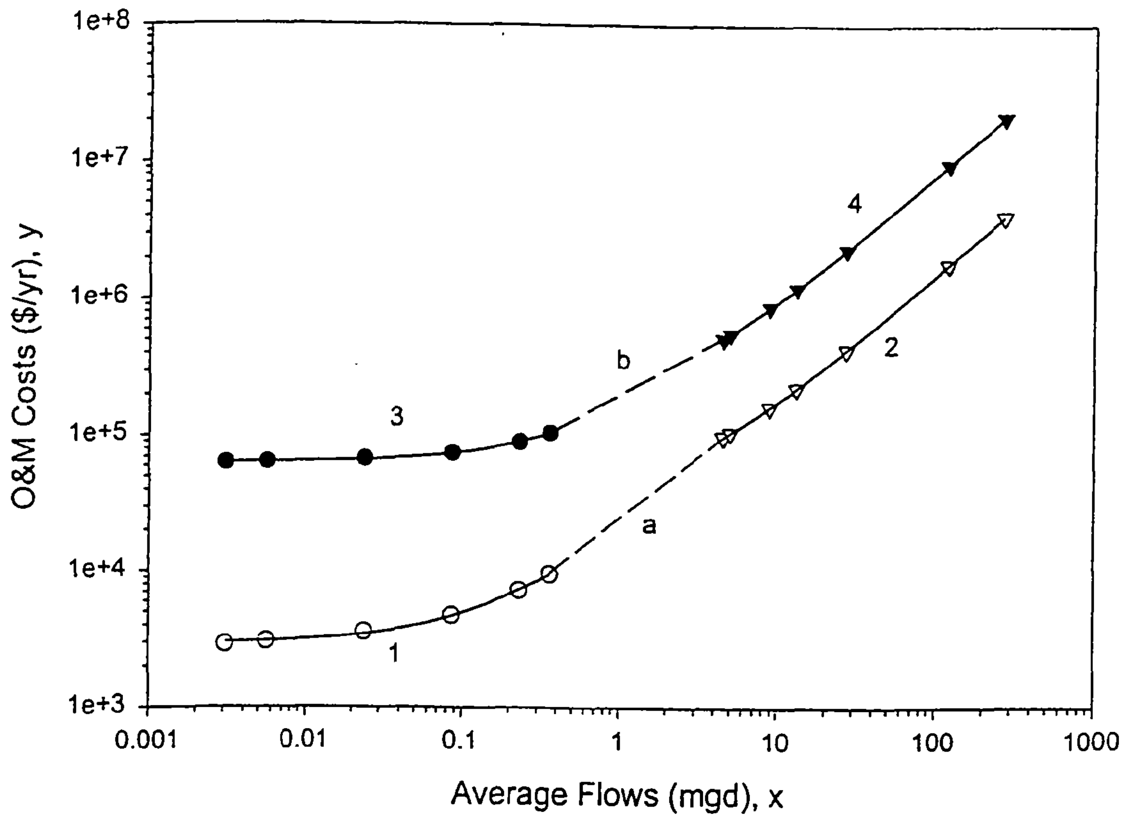
a. $y = 17479x - 3483$	0.36 - 4.5 mgd
1. $y = -302.31x^2 + 7299x + 220$ $R^2 = 1$	0.003 - 0.36 mgd
2. $y = -0.3972x^2 + 14950x + 7906$ $R^2 = 1$	4.5 - 270 mgd

Figure D-3
Capital Costs for Lime Softening



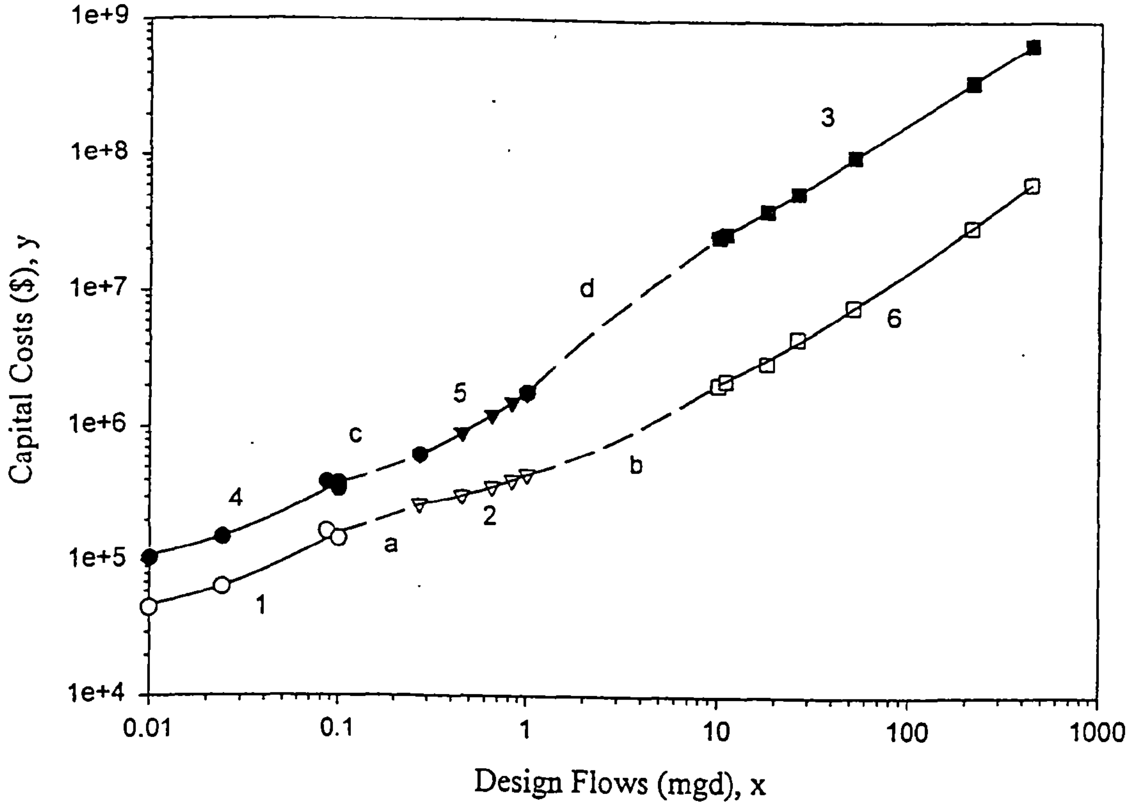
Accessories Costs	**Applicable Flow Range**
a. $y = 331477x + 52533$	1 - 10 mgd
1. $y = 104084 + 380454x - 100528x^2$ $R^2 = .99$	0.01 - 1 mgd
2. $y = 1967171 + 140479x - 46.61x^2$ $R^2 = .99$	10 - 430 mgd
Removal Costs	
b. $y = 1199712x - 519736$	1 - 10 mgd
3. $y = 204540 + 421712x + 53724x^2$ $R^2 = 0.99$	0.01 - 1 mgd
4. $y = 8187348 + 330434x - 143x^2$ $R^2 = 0.99$	10 - 430 mgd

Figure D-4
O&M Costs for Lime Softening



Accessories Costs	Applicable Flow Range
a. $y = 21470x + 1762$	0.36 - 4.5 mgd
1. $y = 2931 + 20690x - 6849x^2$, $R^2 = .99$	0.003 - 0.36 mgd
2. $y = 31465 + 14869x + 0.0082x^2$, $R^2 = .99$	4.5 - 270 mgd
Removal Costs	
b. $y = 101406x + 68702$	0.36 - 4.5 mgd
3. $y = 62903 + 128682x - 38736x^2$, $R^2 = 0.99$	0.003 - 0.36 mgd
4. $y = 161285 + 80863x - 6.96x^2$, $R^2 = 0.99$	4.5 - 270 mgd

Figure D-5
Capital Costs for Reverse Osmosis



● Removal Cost
○ Accessories Cost

Equation

a. $y = 587713x + 104772$
b. $y = 187950x + 258005$

1. $y = 34570 + 1289740x$
   $R^2 = 0.94$
2. $y = 197258 + 243872x + 4825.19x^2$
   $R^2 = 0.99$
3. $y = 7682317 + 1836106x - 648.7x^2$
   $R^2 = 0.99$

c. $y = 1395912x + 240744$
d. $y = 2686316x - 884650$

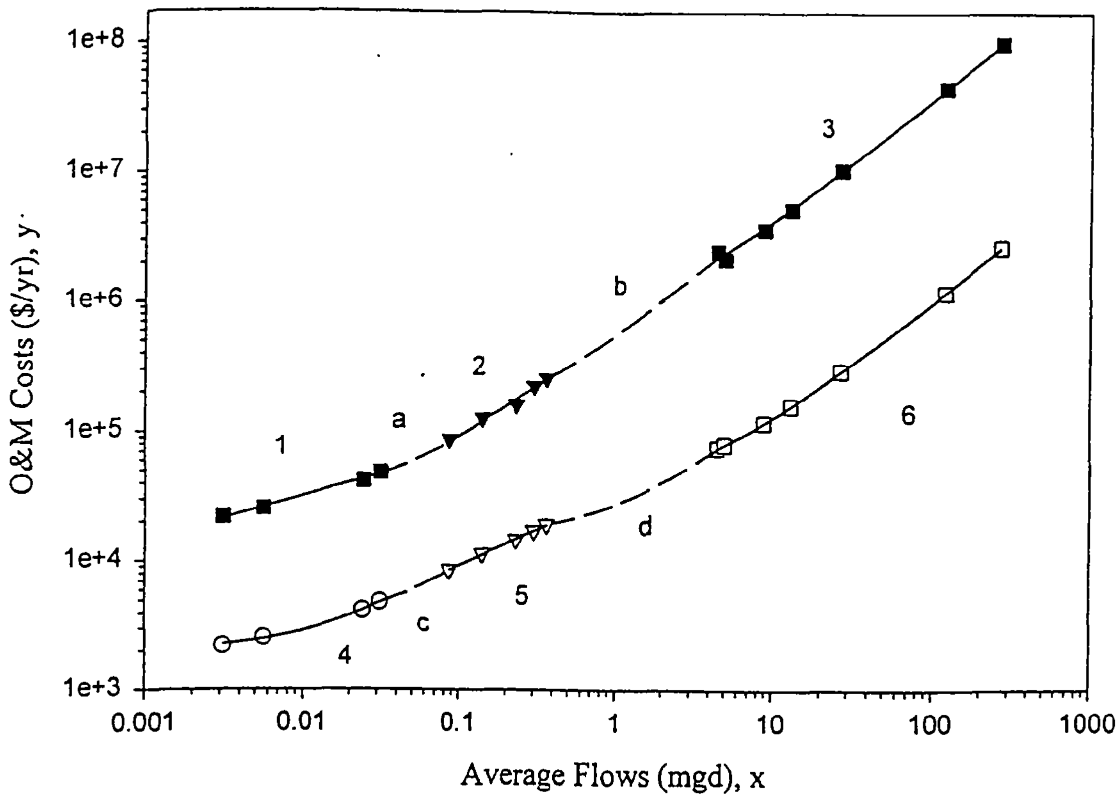
4. $y = 80395 + 2999395x$
   $R^2 = 0.94$
5. $y = 182042 + 1610996x + 8628.2x^2$
   $R^2 = 0.99$
6. $y = 745567 + 138955x + 23.86x^2$
   $R^2 = 0.99$

Applicable Flow Range

1. 0.01 - 0.1 mgd
2. 0.27 - 1 mgd
3. 10 - 430 mgd
4. 0.01 - 0.1 mgd
5. 0.27 - 1 mgd
6. 10 - 430 mgd

a. 0.1 - 0.27 mgd
b. 1 - 10 mgd
c. 0.1 - 0.27 mgd
d. 1 - 10 mgd

Figure D-6
O&M Costs for Reverse Osmosis



Equation	Applicable Flow Range
Removal Costs	
a. $y = 27350 + 641036.8x$	1. 0.003 - 0.03 mgd
b. $y = 78049.5 + 481380.9x$	
1. $y = 157604x^{0.3476}$, $R^2 = 0.99$	2. 0.09 - 0.36 mgd
2. $y = 558613.5x^{0.7817}$, $R^2 = 0.99$	3. 4.5 - 270 mgd
3. $y = 580418.4 + 369743.5x$, $R^2 = 0.99$	4. 0.003 - 0.03 mgd
Accessories Costs	5. 0.09 - 0.36 mgd
c. $y = 2742 + 66502.2x$	
d. $y = 13998 + 13572.1x$	
4. $y = 1965 + 92397.3x$, $R^2 = 0.99$	6. 4.5 - 270 mgd
5. $y = 33353.8x^{0.5568}$, $R^2 = 0.99$	a. 0.03 - 0.09 mgd
6. $y = 30485 + 9908.3xx$, $R^2 = 0.99$	b. 0.36 - 4.5 mgd
	c. 0.03 - 0.09 mgd
	d. 0.36 - 4.5 mgd

● Removal Cost
○ Accessories Cost

APPENDIX E

ADDITIONAL CAPITAL COSTS

Table F1 - Coagulation Filtration Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$37,259	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Filtration Structures	$21,154	$21,934	$25,442	$26,166	$34,851	$46,150	$57,547	$67,047	$75,603	$103,411	$192,515	$298,330	$318,679	$437,974	$574,353	$942,611	$2,464,267	$4,007,457
Additional Backwash Pumps	$10,407	$10,798	$11,373	$11,436	$11,870	$12,118	$12,284	$12,377	$12,456	$47,975	$82,394	$137,237	$147,784	$163,744	$163,744	$163,744	$163,744	$163,744
Additional Raw Water Pumps	$11,822	$11,974	$12,656	$12,797	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$99,396	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,822	$11,974	$12,656	$12,797	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$216,695	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Coagulant Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$41,947	$57,813	$68,323	$70,344	$82,997	$97,458	$142,651	$301,048	$519,313
Backup Sulfuric Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$87,423	$161,514	$253,673	$271,396	$369,366	$464,947	$708,793	$1,718,647	$2,691,389
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$39,146	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$15,798	$26,892	$29,025	$43,958	$61,025	$114,358	$453,558	$922,892
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$157,983	$268,917	$290,250	$439,583	$610,250	$1,143,583	$4,535,583	$9,228,917
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242	$85,242

Table F2 - Enhanced Coagulation Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Backup Coagulant Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$41,947	$57,813	$68,323	$70,344	$82,997	$97,458	$142,651	$301,048	$519,313
Backup Sulfuric Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$87,423	$161,514	$253,673	$271,396	$369,366	$464,947	$708,793	$1,718,647	$2,691,389
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$39,146	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055

Table F3 - Direct Filtration Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$22,926	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Filtration Structures	$20,597	$20,597	$20,597	$20,597	$34,851	$46,150	$57,547	$67,047	$75,603	$103,411	$192,515	$192,525	$318,679	$437,974	$574,353	$942,611	$2,464,267	$4,007,457
Additional Backwash Pumps	$10,798	$11,373	$11,436	$11,879	$11,870	$12,118	$12,284	$12,377	$12,456	$47,975	$82,394	$82,399	$147,784	$163,744	$163,744	$163,744	$163,744	$163,744
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$61,760	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$122,505	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Coagulant Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$41,947	$57,813	$57,814	$70,344	$82,997	$97,458	$142,651	$301,048	$519,313
Backup Sulfuric Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$87,423	$161,514	$161,523	$271,398	$369,366	$464,947	$708,793	$1,718,647	$2,691,389
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$23,929	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$14,776	$24,761	$26,682	$40,124	$55,486	$103,493	$408,820	$831,285
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$147,757	$247,613	$266,816	$401,236	$554,860	$1,034,933	$4,088,200	$8,312,847
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244	$85,244

Table F4 - In-Line Filtration Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$22,926	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Filtration Structures	$20,597	$20,597	$20,597	$20,597	$34,851	$46,150	$57,547	$67,047	$75,603	$103,411	$192,515	$192,525	$318,679	$437,974	$574,353	$942,611	$2,464,267	$4,007,457
Additional Backwash Pumping Capacity	$10,798	$11,373	$11,436	$11,879	$11,870	$12,118	$12,284	$12,377	$12,456	$47,975	$82,394	$82,399	$147,784	$163,744	$163,744	$163,744	$163,744	$163,744
Additional Raw Water Pumping Capacity	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$61,760	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumping Capacity	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$122,505	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Coagulant Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$41,947	$57,813	$57,814	$70,344	$82,997	$97,458	$142,651	$301,048	$519,313
Backup Sulfuric Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$87,423	$161,514	$161,523	$271,396	$369,366	$464,947	$708,793	$1,718,647	$2,691,389
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$23,929	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$14,605	$24,406	$26,291	$39,484	$54,562	$101,682	$401,360	$816,009
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$146,052	$244,062	$262,908	$394,842	$545,623	$1,016,816	$4,013,599	$8,160,091
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245	$85,245

Table F5 - Lime Softening Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$22,926	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Filtration Structures	$20,597	$20,597	$20,597	$20,597	$34,851	$46,150	$57,547	$67,047	$75,603	$103,411	$192,515	$192,525	$318,679	$437,974	$574,353	$942,611	$2,464,267	$4,007,457
Additional Backwash Pumps	$10,798	$11,373	$11,436	$11,879	$11,870	$12,118	$12,284	$12,377	$12,456	$47,975	$82,394	$82,399	$147,784	$163,744	$163,744	$163,744	$163,744	$163,744
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$61,760	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$122,505	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Polymer Feed System	$2,679	$3,273	$5,348	$5,558	$8,298	$9,922	$11,727	$12,842	$13,895	$49,585	$69,378	$69,380	$91,163	$107,213	$121,013	$151,070	$240,751	$304,829
Backup Ferrous Sulfate Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$16,167	$22,756	$22,757	$30,115	$36,440	$43,676	$66,267	$213,415	$405,794
Backup Lime Feed System	$1,814	$2,445	$4,494	$4,474	$4,209	$5,233	$5,789	$5,973	$6,046	$156,882	$203,202	$203,206	$252,893	$269,338	$285,858	$337,474	$550,597	$665,186
Backup Liquid CO_2 Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$58,997	$74,485	$74,488	$110,850	$152,728	$215,763	$409,728	$1,566,384	$3,089,003
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$15,862	$26,963	$29,098	$44,078	$61,198	$114,698	$454,957	$925,293
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$158,623	$269,634	$290,983	$440,782	$611,982	$1,146,981	$4,549,571	$9,252,929
Permitting (Low Estimate)	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624	$24,624
Permitting (High Estimate)	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295	$79,295

Table F6 - Enhanced Lime Softening Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Backup Ferrous Sulfate Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$16,167	$22,756	$22,757	$30,115	$36,440	$43,676	$66,267	$213,415	$405,794
Backup Lime Feed System	$1,814	$2,445	$4,494	$4,474	$4,209	$5,233	$5,789	$5,973	$6,046	$156,882	$203,202	$203,206	$252,893	$269,338	$285,858	$337,474	$550,597	$665,186
Backup Liquid CO_2 Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953	$58,997	$74,485	$74,488	$110,850	$152,728	$215,763	$409,728	$1,566,384	$3,089,003

Table F7 - Anion Exchange Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$22,926	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$61,760	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$122,505	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$23,929	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$12,748	$23,850	$94,463	$192,166
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$127,478	$238,505	$944,633	$1,921,665
Permitting (Low Estimate)	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924
Permitting (High Estimate)	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599	$79,599

Table F8 - Cation Exchange Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$37,259	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Raw Water Pumps	$11,822	$11,974	$12,656	$12,797	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$99,396	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,822	$11,974	$12,656	$12,797	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$216,695	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$39,146	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,000	$12,748	$23,850	$94,463	$192,166
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$127,478	$238,505	$944,633	$1,921,665
Permitting (Low Estimate)	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924	$24,924
Permitting (High Estimate)	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600	$79,600

Table F9 - Reverse Osmosis Additional Capital Costs

Line Item	Design Flow (mgd)																	
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1	1.8	4.8	10	11	18	26	51	210	430
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$14,663	$22,925	$22,926	$40,016	$59,104	$79,295	$124,395	$218,168	$300,098
Additional Backwash Pumps	$10,798	$11,373	$11,436	$11,879	$39,608	$40,365	$40,919	$41,229	$41,492	$47,975	$82,394	$82,399	$147,784	$163,744	$163,744	$163,744	$163,744	$163,744
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$39,606	$61,756	$61,760	$106,635	$152,031	$203,913	$366,044	$1,393,594	$2,772,069
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788	$68,150	$122,496	$122,505	$234,810	$344,021	$442,018	$748,261	$2,726,588	$5,519,520
Backup Sodium Hydroxide Feed System	$1,480	$1,848	$3,344	$6,361	$7,073	$7,826	$8,356	$8,427	$8,637	$15,148	$23,928	$23,929	$42,072	$61,837	$77,251	$116,143	$273,522	$422,055
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$10,000	$10,000	$10,000	$10,136	$13,768	$25,116	$97,290	$197,154
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$101,362	$137,676	$251,158	$972,900	$1,971,537
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252	$85,252

Table F10 - Electrodialysis Reversal Additional Capital Costs

Line Item	Design Flow (mgd)								
	0.01	0.024	0.087	0.1	0.27	0.45	0.65	0.83	1
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872	$4,872
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814	$16,542	$18,529	$20,544	$22,788
Backup Sulfuric Acid Feed System	$1,359	$1,610	$2,310	$2,423	$3,904	$4,928	$5,578	$5,852	$5,953
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$10,000
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000	$100,000
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,253	$85,253	$85,253	$85,253	$85,253	$85,253	$85,253	$85,253	$85,253

Table F11 - Greensand Filtration Additional Capital Costs

Line Item	Design Flow (mgd)				
	0.01	0.024	0.087	0.1	0.27
Disinfection of Finished Water	$4,872	$4,872	$4,872	$4,872	$4,872
Additional Filtration Structures	$20,597	$20,597	$20,597	$20,597	$34,851
Additional Backwash Pumps	$10,798	$11,373	$11,436	$11,879	$11,870
Additional Raw Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814
Additional Finished Water Pumps	$11,714	$11,714	$11,714	$11,714	$14,814
Backup Potassium Permanganante Feed System	$1,359	$1,610	$2,310	$2,423	$3,904
Land (Low Estimate)	$1,000	$1,000	$1,000	$1,000	$1,000
Land (High Estimate)	$100,000	$100,000	$100,000	$100,000	$100,000
Permitting (Low Estimate)	$30,572	$30,572	$30,572	$30,572	$30,572
Permitting (High Estimate)	$85,254	$85,254	$85,254	$85,254	$85,254