THE EFFECT OF TRADABLE DISCHARGE PERMIT (TDP)
PROGRAMS ON THE RELIABILITY OF WATER QUALITY IN RIVERS

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ABSTRACT

Tradable Discharge Permit (TDP) programs have shown, both in practice and in theory, to have tremendous potential as cost-effective methods of pollution control. Nevertheless, there are still many uncertainties regarding TDP programs that if not adequately addressed, might impair their success. Concerns range from issues of market failure that prevents optimal trading, to political agendas that differ from a typical TDP program in their priorities, to modeling difficulties that might cause erroneous predictions of cost savings and environmental performance. The hopelessness of trying to overcome these concerns all at once is recognized. And therefore, apart from a brief discussion where the more common of these uncertainties are identified and discussed, attention is focused only on the uncertainty associated with environmental modeling, specifically that associated with the stochastic aquatic environment.

Numerous studies have been carried out to predict the potential impacts of TDP programs, whether positive or negative, on the environment they are intended to protect. These studies have been invaluable in laying essential groundwork for the further understanding and actual implementation of such programs. However, many of these studies assumed deterministic environmental models when in reality nothing is ever constant. The environment is an open system vulnerable to, amongst many other agents, weather variations and changes in microbial behavior. It is therefore, this study's goal to attempt to advance a step forward by re-assessing those same questions asked many times before, but this time without disregarding the stochastic nature of the environment.

The Willamette and Athabasca Rivers in Oregon, USA and Alberta, Canada, respectively are used as example case studies. These systems are simulated to predict how they might respond if discharge permit trading were implemented. The Mean-Value First-Order Second-Moment (MFOSM) method is used to evaluate the reliability of each system's dissolved oxygen (DO) concentration meeting set standards, as a function of its BOD wasteload distribution and environmental randomness. The results show that trading does indeed influence environment quality. For the Willamette River, trading improves the water quality reliability. For the Athabasca River, trading makes the reliability worse. However, these effects are quite minimal in that, for any target reliability to be achieved that is reasonable, trading is found not to change the reliability significantly in comparison to that attained under a policy of no trading.

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1.0 INTRODUCTION

As the need to protect the environment becomes more obvious, the proper planning and management of increasingly scarce environmental resources becomes more urgent. Effective environmental management involves the implementation of policies that are able to safeguard the environment, but without sacrificing economic development. Needless to say, there exists a tradeoff between environmental quality, and the cost of achieving and maintaining that quality.

The formulation of conscientious policies often requires predictions of the actions of certain parties and how those actions might affect environmental quality. The fickleness of human behavior makes it difficult for such predictions to be accurate. This is further complicated by the stochastic nature of the environment. In general, waste discharge regulations can be categorized into two groups. The first is the more traditional and familiar "command-and-control" policies; and the second is the more innovative but less tested "market-based" policies.

While command-and-control policies have served well in the past, and even presently, they have faced heavy criticism for not giving industry sufficient flexibility, which results in economic inefficiency. Such policies, that place explicit restrictions on allowable levels of emissions and/or force the use of specific pollution abatement technologies, simply do not give industry the freedom to adopt cost-saving measures as it sees appropriate. Neither do these policies give any incentive for industry to reduce their pollution levels beyond the standards required by law.

In recent years, market-based policies have been gaining popularity as alternatives that address these shortcomings. One such policy is the utilization of tradable discharge permits to regulate polluters. Under this policy, the action to pollute is seen as a property right with tangible value that is transferable. Theoretical studies [Montgomery, 1972; Brill et al, 1984; Baumol & Oates, 1988], as well as practical experience [Schmalensee et al, 1998; Stavins, 1998; Schwarze & Zapfel, 2000], have proven the tremendous potential Tradable Discharge Permit (TDP) programs carry as a cost-effective means of pollution control.

However, there is still much uncertainty of the inner workings and implications of TDP programs that if not adequately addressed, might impair their success. These uncertainties, of which some are quantifiable but most are not, are as random as they are diverse. Concerns range from issues of market failure that prevents optimal trading, to political agendas that differ in their priorities, to modeling difficulties that might cause erroneous estimations of cost savings and environmental performance.

This study attempts to address some of these concerns. Naturally, it is hopeless to try to overcome these issues all at once. And thus, apart from a brief review where the more common of these issues are identified and discussed, attention is focused only on the ones that are less abstract and more tangible. More specifically, for the time being, uncertainties of politics, psychology, trading and such are assumed negligible and only uncertainty related to the stochastic environment is considered. For now, it is conveniently assumed that perfect market conditions apply such that trading ultimately leads to some predictable, deterministic, least cost equilibrium.

Due to the nature of environmental permit trading programs, where the locations of discharge may change, it is advantageous to know *a priori* how trading might impact environmental quality. Regardless of its cost efficiency, a program that fails to protect the environment falls short of its primary objective. To assess this question of how trading might impact the environment, mathematical models are used to simulate how the environment might respond to certain market behaviors. However the task of developing an adequately accurate environmental-response model, and collecting the required data, is not without difficulty. Many of the studies carried out in the past [Montgomery, 1972, Eheart, 1980; Brill et al, 1984; Eheart et al, 1987] applied deterministic models that neglect the stochastic nature of the environment. This negligence, though convenient and perhaps computationally necessary in the past, led to results that did not wholly represent reality. Thus, the primary objective of this study is to re-examine this issue of the environmental impact of permit trading, but this time with stochastic models that are better able to characterize the true state of the environment.

To achieve the objectives of this study, the cases of the Willamette River in Oregon, USA and the Athabasca River in Alberta, Canada are used as example case studies. Both systems are modeled to observe how they might behave if permit trading were allowed. In both cases, environmental quality is measured as the reliability of the dissolved oxygen (DO) concentration, subject to the BOD wasteloads discharging into the river, meeting a certain pre-set standard, where reliability can be defined as the probability of the system performing as desired or better. The Mean-Value First-Order Second-Moment (MFOSM) method, a method based on first-order approximations of the Taylor series, is used to estimate the reliability. Essentially, the goal is to make some quantitative comparison between the reliability of the system before trading, and the reliability after trading. And with that, to gain some insight on the suitability of permit trading programs for environmental preservation.

Following this introduction, Chapter 2.0 gives a review of TDP programs in general as well as a discussion of the uncertainties obstructing their successful implementation, Chapter 3.0 outlines the theory used, Chapter 4.0 explains the details and methodology of the numerical work done to illustrate the ideas developed, Chapter 5.0 presents and discusses the results obtained and finally Chapter 6.0 summarizes and concludes this study.

2.0 LITERATURE REVIEW

Of late, the trading of environmental permits has been a popular topic of discussion among policy-makers and economists, as well as engineers. This section strives to give an overview of the literature that is available concerning this subject. Section 2.1 introduces the concept of permit trading with emphasis on its tremendous potential as a cost-effective means of pollution control. Section 2.2 reviews three practical implementations of permit trading programs to illustrate that such programs do not necessarily work as well in practice as they do in theory. And finally Section 2.3 examines why the observations made in Section 2.2 are as they are, with the hope of gaining a better understanding of the many uncertainties facing permit trading programs that may hinder their success.

2.1 Discharge Permit Trading Programs

The notion of discharge permit trading as a pollution control tool was first proposed more than thirty years ago by, among others, Dales [1968] and Crocker [1966]. Since then, it has grown from being a mere theoretical concept to becoming a reality that is increasingly attracting the attention of economists, scientists and legislators. Permit trading is a form of market-based policy that uses economic incentives to achieve pollution control, without the high costs normally associated with the more established command-and-control regulations. Under permit trading programs, the action to pollute is seen as a property right, and is therefore transferable and with tangible value. Participants in a permit trading program are each initially allotted an amount of permits, after which they may either buy additional permits from, or sell excess permits to, each other. Generally, in an ideal market, the buyers are those with relatively high waste abatement costs, while the sellers are those with relatively low waste abatement costs. In a trading program, the total number of permits is capped, and this cap is sometimes slowly reduced over time depending on the objectives of the program.

Permits can initially be either sold, or distributed without charge, by the governing authority to the dischargers. If the initial permits are to be sold, one method is to auction off the permits. A form of auction that discourages bidder collusion and is administratively straightforward is the single-price auction [Eheart et al, 1980]. In a single-price auction, each discharger is required to submit a binding schedule listing the quantity of permits it is willing to purchase at any given price. All permits are then sold at the market clearing price, which is the price at which the aggregate demand of the market equals the total amount of permits available.

However, as pointed out by Eheart et al [1980], a more politically feasible method might be to allocate the initial permits without cost to the dischargers, who are then encouraged to re-distribute the permits among themselves via auctions or other means. The initial allocation should be carried out in an equitable manner, though equity is sometimes not easily defined. The governing authority also bears the responsibility of identifying which parties qualify to receive free permits, and which do not.

More thorough discussions on alternative methods to initially allocate the permits, and their respective advantages and disadvantages, as well as other relevant issues are made by Eheart et al [1980], David et al [1980] and Lyon [1982].

Naturally, the worth of a permit would depend upon its definition. The most common definition used is that that defines a permit as an entitlement to discharge a specified amount of pollutant into the environment over a specified period of time. However, there has been suggested variations of that original definition, such as that by Eheart and Brill [1983] that defines a permit as the right to deplete the quality of the environment at a specific location by a specified amount. And that by Eheart et al [1987] that defines a permit as being seasonal, where a permit holder is allowed to discharge at a higher rate during times of the year when the assimilative capacity of the environment is larger, but at a lower rate during other more critical times.

The major attraction that permit trading programs offer is that pollution control that is driven by fee market forces will, under ideal market conditions, be less costly to society as a whole, than when dictated by force of rule, as under command-and-control policies. This is especially so for systems where locational effects are negligible i.e. the location of a given discharge does not affect environmental quality. For such systems, the permit market equilibrium coincides with the least cost solution [Montgomery, 1972], where the least cost solution is the combination of waste abatement levels that incurs the least amount of cost to attain a particular level of environmental quality. In short, permit trading programs have the capability, provided that certain conditions are present, to achieve ambitious environmental goals that might be economically unachievable under other policy programs. Practical experience confirms this conclusion [Schmalensee et al, 1998;Stavins, 1998; Schwarze & Zapfel, 2000].

Permit trading programs have other advantages too. For instance, in relation to other market-based policies, permit trading does not place the sometimes excessive financial burden on either the dischargers or the governing authority that effluent taxes place on the dischargers, and subsidies on the governing authority [Eheart & Brill, 1983]. Furthermore, from an ethical viewpoint, permit trading is likelier to win public support than subsidies. Tradable permits, which can be viewed as "licenses to pollute" are surely a lesser evil than subsidies that essentially are "bribes not to pollute". Considering also, most individuals' natural aversion to any new form of taxes, it is also likely that those in industry would prefer permit trading to environmental taxes. Of course, industry would generally pay less overall under trading for waste treatment than under a tax system if the tax rate were set sufficiently high to equal the marginal abatement cost.

Permit trading programs also provide incentive for dischargers to enhance the efficiency of their waste abatement facilities [Eheart & Brill, 1983]. By reducing their marginal abatement costs and consequently increasing their ability to attain higher degrees of pollution control, dischargers are able to earn credits, which they can then sell to other dischargers with higher marginal costs. This gives the net benefit of overall cost savings, as well as improved technology.

Additionally, permit trading programs are better able to safeguard environmental quality in the face of industrial growth [Eheart & Brill, 1983]. Those seeking to establish new pollution sources, or expand existing ones, may simply purchase permits from other dischargers who are looking to sell their excess credits. Since the total number of permits is kept constant, the environment is protected in the sense that the total amount of pollution discharged remains the same regardless of the number of sources. This is in contrast to command-and-control programs where there is no constraint to ensure that environmental quality is maintained each time a newcomer appears, or an existing discharger chooses to increase production. Rather, compliance standards under command-and-control programs probably need to be revised regularly to accommodate industrial growth.

Finally, permit trading programs have the advantage of being administratively less demanding. Unlike command-and-control programs where the regulatory authority holds all governing power, permit trading decentralizes the decision-making process and gives more responsibility to the private sector. The market is utilized to coordinate decisions such that long-term efficient solutions are evolved [Zerlauth & Schubert, 1999]. This removes the need for the governing authority to know and regulate every single detail of the problem. After the initial set-up that might require more effort, the regulatory authority can withdraw into a more passive role as market watchdog and monitoring agent [Schwarze & Zapfel, 2000], whose duties include maintaining a registry of permits to keep track of trades.

2.2 Practical Implementations of Permit Trading

Although not the first, the most prominent permit trading program to date is perhaps the Acid Rain SO_2 Emissions Trading Program, a national scale program under the administration of the United States Environmental Protection Agency (US EPA). Much literature [Schmalensee et al, 1998; Stavins, 1998] has touted the success of this program, which has often times been cited as proof that permit trading works not just in theory but in reality too. While it is true that permit trading has demonstrated ts immense potential, it is important to realize that not all permit trading programs implemented have succeeded and some of those that have, have not behaved as they ideally could have. To illustrate this point, the following sub-sections review three practical implementations of permit trading, the first two applied to airshed management and the last to watershed management.

2.2.1 The Acid Rain SO_2 Emissions Trading Program

The Acid Rain SO_2 Emissions Trading Program was instituted under Title IV of the Clean Air Act Amendments of 1990, and is currently still ongoing. This program seeks to reduce the occurrence of acid rain by reducing sulfur dioxide (SO_2) emissions from electricity generating units across the continental United States. It aims to reduce SO_2 emissions to roughly half their 1980 levels in the most cost-efficient, yet equitable and politically acceptable, fashion possible.

The SO_2 Emissions Trading Program is implemented in two phases, Phase I (1995-1999) and Phase II (2000-2009). Under Phase I, 263 of the worst polluting large generating units were targeted and their aggregate annual emissions capped, while under Phase II, virtually all other generating units are targeted as well and their aggregate emissions restricted too. Under this program, each permit allows for the emission of one ton of SO_2, and is valid for a specific calendar year. Unused permits may be carried forward for future use. The total emissions of a plant may not exceed the number of permits it holds. The penalty should there be a violation is a fine of US$2000 per ton exceeded, and the forfeiture of an equivalent number of tons the following year.

Observations so far give all indication that the SO_2 Emissions Trading Program is a success. Short-term environmental goals have been met and exceeded. There was a sharp drop in SO_2 emissions in 1995, the first year of the program. Indeed, aggregate emissions in 1995 was about 39% less than the total amount of permits issued, and in 1996 about 33% less [Schmalensee et al, 1998]. Annual compliance costs have been estimated to be up to US$1 billion less than what they would be under command-and-control alternatives [Stavins, 1998].

Permit prices have also been lower than expected. This can be seen as a positive sign of substantive physical and technological advancement. Permit trading could have accelerated the numerous innovations in scrubber technology that, together with the deregulation of the railroad industry, have driven down the effective marginal cost of SO_2 abatement. With transportation costs decreased, utilities in the East and Midwest now have the option of switching to low-sulfur Western coal from the Powder River Basin, when previously they were more or less economically limited to more local high-sulfur coal [Conrad & Kohn, 1996; Schmalensee et al, 1998]. Schmalensee et al [1998] estimated the average cost to reduce emissions by switching to more expensive low-sulfur coal to be around US$153 per ton, while reduction by scrubbing costs around US$265 per ton.

Another sign of success is the low transaction costs and increasing trading volume in the SO_2 permit market, which are indications of a well-formed market. Auctions by the Chicago Board of Trade, as well as the presence of private brokers such as Fieldston and Cantor Fitzgerald, have helped developed a working market where buyers and sellers are able to easily identify each other [Schemalensee et al, 1998; Solomon, 1999]. According to Zorpette [1994], commissions as low as US$1.75 per permit traded have been reported. And according to Schemalensee et al [1998], trading volume in the private market has increased from 130,000 in 1993 to 226,000 in 1994 to 1.6 million, 4.9 million and 5.1 million in 1995, 1996 and 1997 respectively.

However, the SO_2 Emissions Trading Program is not entirely without weakness. The lower than expected permit prices can be interpreted negatively too. Some [Coggins & Swinton, 1996; Conrad & Kohn, 1996; Schwarze & Zapfel, 2000] have argued it to be the result of regulatory overlap. Due to the precedence of local regulations that are more stringent, some high cost abaters have been forced to sell their permits at prices below their marginal abatement costs. Thus potential buyers become sellers instead. This explains cases like that of Wisconsin utilities, which, bounded by state acid rain legislation, were significant sellers of Phase I permits.

Another weakness of the program is the issuance of excess permits above the original cap. This is said to have resulted in lower than anticipated trading volume [Conrad & Kohn, 1996], not to mention compromised environmental goals. In 1995, 20% of the 8.7 million permits in circulation were awarded as bonuses to certain utilities for making early emissions reduction efforts, switching to renewable energy sources, using advanced clean coal technologies etc. [Schwarze & Zapfel, 2000]. Definitely this diminishes the overall efficiency of the program but can be partially justified as necessary to garner necessary political support.

2.2.2 The Regional Clean Air Incentives Market (RECLAIM)

Southern California, especially the South Coast Basin surrounding Los Angeles, had perhaps the worst air quality in the country and was the worst non-attainment area where federal and national standards were constantly violated, especially for ozone and particulate matter. This is due mainly to its climate and geography as well as its above average urban and industrial growth. Whatever environmental progress made was sooner or later offset by economic growth. For over 20 years before RECLAIM, costly attempts were made to bring the region into compliance via various forms of command-and-control regulations. In 1990, the average marginal NO_x abatement cost for power plants in Los Angeles was about US$25,000 per ton, compared to US$5,000 per ton in the United States [Zerlauth & Schubert, 1999].

RECLAIM was introduced in 1994, under the jurisdiction of the South Coast Air Quality Management District (SCAQMD), and is set to run until 2010. It regulates sulfur oxides (SO_X) and nitrogen oxides (NO_X), which are smog-causing pollutants. RECLAIM does not allow inter-pollutant trading. Its primary objective is to reduce the aggregate emissions of NO_x by 75%, and SO_x by 60% from their 1994 starting values but without incurring to high a cost. Unlike the SO_2 Emissions Trading Program, RECLAIM is a multi-industry plan covering dischargers from a wide array of industries including ceramics, food, glass, tiles and furniture [Schwarze & Zapfel, 279]. Due to the non-uniform mixing characteristic of the two pollutants, RECLAIM divides the region into two trading zones i.e. coastal and inland, with some restriction on the direction a trade may take. RECLAIM also does not allow banking, which means that a permit is only valid for a specific year and unused permits must be retired.

Judgment on RECLAIM's performance has been mixed. On one hand, statistics imply it to be a success, or at least a partial success. On the other hand, deeper examination shows an under-developed market and regulatory uncertainty. 1994 to 1996 statistics from the SCAQMD [1998] show aggregate NO_X and SO_X emissions to be lower than the total amount of permits issued and on the overall, to be following a decreasing trend. The SCAQMD [1996] also reported the development of a healthy market with over 400 trades, or 100,000 tones of pollutants, as of November 1996. Permit prices were also much lower than expected [Zerlauth & Schubert, 1999].

However, as pointed by Zerlauth and Schubert [1999] and Kiler et al [1997], the lower than expected aggregate emissions can be explained by the overallocation of permits, rather than any significant decrease in emissions. RECLAIM was launched at a time when California was experiencing a recession, which means that many facilities were operating at below-average production levels at that time, and thus emitting less than normal. Therefore, the permits were allocated based on emissions data for years when the facilities were operating at higher levels, so not to restrict growth when the economy recovered. This explains the seeming over-compliance, as well as the lower than anticipated permit prices.

It was also shown that while there has been active trading during the early years of the program, many of the trades were "no-price" trades [Kiler et al, 1997]. No-price trades are trades where permits are transferred from one facility to another at no cost to the buyer. Though some of these no-price trades were legitimate intra-company transactions that resulted in cost savings, others were simply the selling of permits to the broker or the return of unsold permits by the broker. No-price trades were also due to the dumping of excess permits to non-RECLAIM facilities, and/or non-profit environmental groups and such, to avoid having to pay unnecessary fees for unused permits and/or for public relation reasons. During the first year and a half of the program, permit holders were required to pay fees for permits held, including ones that were unused.

Furthermore, the major reason cited for the selling of permits is a decrease in production levels resulting in a decrease in emissions [Kiler et al, 1997]. This is not surprising considering that California was going through a recession during the time when the statistics were compiled. Nonetheless, this does mean that emissions were being reduced not because of improvements in control equipment technology or process design. This does not necessarily mean program failure, but simply a slower than hoped for start.

Nevertheless, a good market mechanism has been set up, even in the absence of a central market authority [Zerlauth & Schubert, 1999]. Majority of the trades are facilitated by private brokers e.g. Cantor Fitzgerald, with transaction costs seen as minimal. An electronic auction program is also available as an alternative trading avenue.

Regulatory uncertainty was also a problem at the program onset, causing market participants to be unsure of their long-term planning [Zerlauth & Schubert, 1999; Klier et al, 1997]. Since the commencement of the program, the regulations and emissions cap were amended several times. Some of these changes were unavoidable due to RECLAIM's experimental nature. For instance, at the beginning of the program, permit holders were required to pay fees proportional to the amount of permits held, including the ones that are unused. However, when it was realized that this requirement caused price fluctuations towards the end of the compliance cycle, this requirement was revised so that permit holders now have to pay fees proportional only to the amount of permits actually used.

2.2.3 The Fox River Trading Program in Wisconsin

The Fox River effluent trading program was launched in 1981, under the authority of the Wisconsin Department of Natural Resources (DNR), and is, at this time, still ongoing. It is the first water quality trading program implemented and perhaps the most well-known to date. It regulates the discharge of Biological Oxygen Demand (BOD) from roughly twenty industrial and municipal facilities along the Fox River in Wisconsin, which is tributary to Green Bay. Most of the industrial facilities are pulp and paper mills, and municipal facilities wastewater treatment plants. The Fox River program is an offset program that primarily seeks to maintain water quality amidst economic growth. The cap on the total allowable amount of BOD discharge is fixed, unlike the more high-profile airshed trading programs where the cap is reduced over time. According to EPA [1996] and Hahn and Hester [1989], a preliminary analysis, carried out in 1979, estimated annual savings of up to US$6.8 million.

Since its inception, only two trades have taken place. The first trade transferred permits from a pulp and paper mill to a municipal wastewater treatment plant [EPA, 1996]. The mill had shut down its wastewater treatment plant, and re-directed its waste to be treated at the municipal plant. The trade was to adjust for this new arrangement. As for the second trade, permits were transferred from a pulp and paper mill to a newly built marina [Jarvie & Solomon, 1998].

This lack of trading volume is probably due to the program's many regulatory restrictions [Hahn & Hester, 1989; EPA, 1996; Woodward et al, 2002]. Trades have to meet the approval of the governing authority before being allowed to take place, and are only allowed under certain conditions such as e.g. the buyer must be a new facility, or an expanding one, or unable to meet discharge limits even when using required technology. Trades that have the sole objective of saving costs are barred. Each potential trade has to pass a review process that could take up to six months, and is only passed if tests show that the redistribution of waste-loads does not cause water quality standards to be violated.

There is also no effective market mechanism in place. Whatever trade that is to take place would be through bilateral negotiations, a process that is time-consuming as well as costly. Effort has to be spent to search for and locate potential trading partners. Furthermore, since whatever savings that could come from trading would be only a very small percentage of the total cost of operation, especially for the pulp and paper mills, there is little motivation for the facilities to spend that extra effort to trade [EPA, 1996].

Nevertheless, considering that the primary goal of the program is not to promote savings but to protect the river's water quality [Hahn & Hester, 1989; EPA, 1996], the program cannot be said to be without success. The program has played, and is still playing, its role by effectively capping the BOD wasteloads entering the river. Furthermore, the program is among the first of such to be implemented and thus, the lessons learnt from it are invaluable.

2.3 Uncertainties Facing Permit Trading Programs

The uncertainties confronting permit trading programs are countless and are responsible for them not performing as well in practice as in theory. The adequate understanding of these uncertainties is imperative for the design of trading programs that are robust and cost effective but yet not disregarding environmental quality and the interests of minority stakeholders.

One major source of uncertainty is the complex makeup of the environment, complicated by its stochastic nature. Modeling difficulties arise from the lack of accurate understanding of natural environmental processes, and from imperfect measurement techniques of ever-changing environmental variables. Environmental models are mathematical simplifications that make too many assumptions, and thus are never perfect. In a permit trading program, it is important to be able to predict beforehand how trading might impact environment quality, and hence the need for reliable environmental models.

Another source of uncertainty is the unpredictability of human behavior that makes it difficult to reliably foretell market performance. The cost effectiveness of TDP programs is only wholly realized when the market functions as envisioned, i.e. when there is active trading between the program participants. Should participating firms decide not to trade, a TDP program is then only as cost effective as a uniform discharge program, or whatever program that forms the basis for the initial allocation of permits. Market imperfection not only causes loss of cost savings, but also makes it difficult to know in advance how permits in a market will move, and thus, how trading might influence environmental quality. In theory [Eheart, 1980; Brill et al, 1984; Eheart et al, 1987] perfect market conditions are assumed where firms will act to maximize profits, transaction costs are absent, and information is freely available. However, in reality, such market conditions hardly ever exist [Atkinson & Tietenberg, 1991; Stavins, 1995].

Market unpredictability may also be due to the banking of emissions credits. Where banking is allowed, as it is under the EPA SO_2 Emissions Trading Program, some firms might choose to retain their excess permits for future use instead of selling them. This is primarily due to their fear that they might not be able to purchase them back in the future if need be, and this in turn is due to uncertainty of future permit prices and of possible regulatory tightening. Market unpredictability is further increased when firms choose to trade internally even when it is more profitable to trade externally. Internal trades, or rather intra-firm trades, are favored when there is no organized market institution, when external trades require regulatory approval, and when the property rights associated with a permit are not clearly defined [Hahn & Noll, 1990].

Political considerations too are important factors in the successful implementation of permit trading programs [Hahn & Noll, 1990; Stavins, 1998]. It is worth bearing in mind that at the end of the day, it is the politicians and bureaucrats who make the final decision as to whether or not a new program being implemented is permit-based. A successful policy is one that balances the objectives of politics with the objectives of economics. A good understanding of the conflicting objectives of the many stakeholders involved is necessary to pave the way for a wider acceptance of permit trading programs.

Of course, these uncertainties thwarting the successful implementation of permit trading programs are too many to address all at once. For this study, attention is therefore focused only on the issues that are deemed more tangible and less abstract, namely the modeling uncertainties associated with the stochastic environment, of which more details are given in the following sub-section. To lay the groundwork for future work, further discussion on the presence of transaction costs in permit markets is also made.

2.3.1 Environmental-Modeling Difficulties

The environment is a complex system that is unfortunately too large and too open to model adequately without difficulty. For modeling purposes, it is usually convenient and many times necessary, to compress environmental behavior into a few parameters and mathematical equations. However, doing so forces assumptions that may not be entirely valid. Errors resulting from such invalid assumptions are sometimes known as Type I errors, as defined by Burges and Lettenmaier [1975].

Nevertheless, assuming that numerical models are adequately able to represent the environment, there will still be errors due to the non-existence of foolproof measuring techniques of variables, such as stream flow, rainfall and concentration. While some parameters like temperature are fairly easily to measure accurately, other parameters like BOD decay coefficients are not as easily so. The stochastic nature of the environment makes this problem worse. Errors stemming from the use of inaccurate parameter values are sometimes known as Type II errors, again as defined by Burges and Lettenmaier [1975].

In permit trading programs, permits will move from one location to another. The movements of these permits, together with the natural fuctuations of the environment, make it very possible for trading to cause environmental degradation. This is especially so for systems where locational effects are significant i.e. environmental quality is strongly influenced by the location of a given discharge. Therefore, it is desirable to be able to anticipate fairly accurately *a priori* how trading might impact environmental quality. To do so, numerical representations of the environment are utilized and hence, it is crucial that whatever errors that might arise from unreliable models and imprecise data are kept minimal.

This issue of the potential impact of trading on environmental quality has many times been addressed by such as Eheart [1980] and Brill et al [1984]. These earlier studies employed deterministic models that assumed an unchanging environment. While this approach is computationally advantageous, it is not without flaw. Though these studies have been invaluable in laying essential groundwork, a more thorough approach would be to use stochastic models that do not neglect the ever-changing state of the environment. Numerous methods to incorporate stochastic uncertainty into multi-objective models have been suggested in literature. Included are ones based on first-order approximations of the Taylor series, of which one of them, the Mean-Value First-Order Second-Moment (MFOSM) method, provides foundation for parts of this study.

Another example of first-order methods is the Advanced First-Order Second-Moment (AFOSM) method. In general, the principal advantage these methods have to offer is their computational simplicity and accessibility. However, this advantage is somewhat diminished by their lesser versatility. First-order methods assume the output variable to be a linear function of the input variable(s), an assumption that will not hold for strongly non-linear systems. Furthermore, when using first-order methods, the probability distributions of the random input and output variables are represented only by their means and variances. This leads to the inability of these methods to accurately represent highly skewed distributions. A more thorough discussion on the pros and cons of first-order methods, as well as an overview of their underlying theory can be found in Kataoka [1963], Yen et al [1986] and Ang and Tang [1984],

One example of first-order methods applied to water resources management is by Tung [1990], who compared MFOSM and AFOSM and found them both to generally give good agreement with Monte Carlo simulation results. However, for extreme probabilities, MFOSM was found to be less reliable, and the AFOSM method superior. Melching and Anmangandla [1992] made a similar comparison and obtained results that confirmed Tung's [1990] findings. More recently, Vasquez et al [2000] used AFOSM coupled with genetic algorithms to optimize the waste-load allocations of a river system. Also, recent work by Maier et al [2001] extended the usefulness of AFOSM from just reliability estimation to estimations of vulnerability and resilience as well. AFOSM has also been used for the sensitivity analysis of complex water quality models, and has shown to be more effective than the traditional method of perturbing one variable at a time [Melching & Yoon, 1996; Melching & Bauwens, 2001].

Further methods of solving stochastic multi-objective systems are those based on Monte Carlo simulation [Meyer et al, 1994; Storck et al, 1997] and others based on multiple system realizations [Morgan, 1993; Ritzel, 1994; Takyi & Lence, 1999]. There is also the Second-Order Reliability Method (SORM) [Madsen et al, 1986]. For more details on the analysis of uncertainty and risk in water quality modeling, refer to Beck [1987], and in policy-making, refer to Morgan and Henrion [1990].

To the best of this author's knowledge, the concepts and methods mentioned above, have not, before this study, been applied directly within the context of permit trading. Nevertheless it has been acknowledged that varying environmental conditions do affect the efficiency of a trading program and that to design a program based on a single worst-case period forces dischargers to treat at levels higher than necessary during other times. To reduce this inefficiency, O'Neil [1983] proposed the use of a time-varying permit plan, whereby a year is divided into a number of periods according to local weather conditions. Within each period, environmental parameters like temperature and stream flow are assumed constant. However, they may change from one period to the next. Under such a plan, permits are dated such that dischargers are allowed to abate less during non-critical periods. Eheart et al [1987] further examined this idea and confirmed that time-varying permits are indeed more cost effective than the conventional invariant ones.

2.3.2 Transaction Costs in Permit Markets

Much has been said in literature regarding the role of transaction costs in TDP markets [Stavins, 1995; Solomon, 1999; Montero, 1997]. There seems not to be any exact definition of transaction costs. Loosely, it may be taken to mean the secondary costs of trading that are not directly related to the buying and selling of permits. This includes, but is certainly not limited to, the cost of gathering information, the cost of searching for potential trading partners, the cost of negotiating new contracts, the cost of brokerage commissions/fees and the cost of modifying existing engineering systems to meet new abatement targets.

Many of the earlier works on permit trading [Montgomery, 1972; Brill et al, 1984; Eheart et al, 1987] ignored transaction costs and assumed perfect market conditions, resulting in overestimations of the cost efficiency of trading, and underestimations of the possibility of market failure. Transaction costs that are too high make it unprofitable for potential buyers or sellers to trade. Even though their marginal abatement costs might be such that trading is an attractive option, the presence of transaction costs might force the overall cost of trading to exceed their original costs of compliance.

One sign of the presence of unhealthily high transaction costs in a permit market is trading volume that is relatively weak. For example, transaction costs may be blamed for the failure of the Fox River TDP program. Due to its many regulatory restrictions that require those interested in trading to endure a lengthy approval process, its entire trading history, as noted above, so far contains only two trades [EPA, 1996; Jarvie & Solomon, 1998; Hahn & Hester, 1989]. On the other hand, the success of EPA's SO_2 Emissions Trading Program, can be partially attributed to a well-formed market where transaction costs are minimal. Regular auctions held by the Chicago Board of Trade, as well as the establishment of private brokers, have ensured the formation of a straightforward trading procedure with little uncertainty [Schemalensee et al, 1998; Solomon, 1999].

A much-cited piece of literature on transaction costs is that by Stavins [1995], who outlined theoretically how transaction costs might negatively affect market equilibrium, causing the cost-efficiency of a trading program to decline. He also proved that, in the presence of transaction costs, the initial distribution of permits does determine the final equilibrium point. Stavins' [1995] model is a basic one with two market participants, both having idealized twice-differentiable cost curves. This work by Stavins [1995] is noteworthy as it is perhaps the first to provide some theoretical foundation to the problem.

Montero [1997] extended Stavins' [1995] model to include trade uncertainty i.e. the uncertainty of a potential trade gaining regulatory approval when such approval is required. For cases where trade uncertainty is an issue, trading decisions are made based on the expected cost of compliance, rather than its deterministic equivalent. Montero [1997] also demonstrated how numerical modeling might be used for more complex cases where there are multiple participants, with discontinuous cost curves and/or the discrete waste abatement variables.

Gangadharan [2000] offers an alternative approach to looking at the problem. Using RECLAIM as a case study, he investigated the effect of transaction costs on the behavior of polluters in terms of their trading probabilities. It was shown that transaction costs do indeed reduce the probability of trading. Gangadharan's [2000] model considers not just the estimated costs of compliance, but also the locations of polluters, the initial permit allocation and the potential for industrial growth.

The above-mentioned articles have definitely contributed greatly to the better understanding of the effects of transaction costs on permit trading. However, these articles were written from an economic perspective that judges the presence of transaction costs to be undesirable as it reduces market efficiency. No effort has been made thus far to evaluate how this reduction in market efficiency might affect environmental performance, either positively or negatively.

3.0 THEORY

The Mean-Value First-Order Second-Moment (MFOSM) method [Kataoka, 1963; Ang and Tang, 1984; Yen et al, 1986] is a method often used to estimate a system's uncertainty and is essentially based on first-order approximations of the Taylor series. Mathematically it is relatively straightforward. It is also computationally simpler than some of the other uncertainty analysis methods proposed in literature [Morgan, 1993; Madsen et al, 1986; Vasquez et al, 2000; Maier et al, 2001]. Though unsuitable for highly non-linear systems, it more than suffices for the purposes of this study. The following sub-sections describe how MFOSM may be applied to water quality modeling, and how it may be further expanded to show the effects of trading on the water quality reliability of a river.

3.1 MFOSM Applied to Water Quality Modeling

MFOSM has been widely applied to water quality modeling by among many others, Tung [1990] and Melching and Anmangandla [1992]. MFOSM is based on first-order approximations of the Taylor series, which for a general multivariate function, f takes the following form.

$$f(X) = f(X^e) + \sum_{i=1}^{n} \frac{(x_i - x_i^e)^1}{1!}\left(\frac{\partial f}{\partial x_i}\right)_{X^e} + \sum_{i=1}^{n} \frac{(x_i - x_i^e)^2}{2!}\left(\frac{\partial^2 f}{\partial x_i^2}\right)_{X^e} + \ldots \quad \text{.......... (1)}$$

where x_i is the i^{th} input variable, x_i^e is x_i evaluated at the expansion point e, X is the x_i vector, X^e is the x_i vector evaluated at the expansion point e and n is the total number of input variables. Like other first-order methods, MFOSM truncates the Taylor series after the first-order term. Therefore, by expanding the function about the mean values of the uncertain elements within the system, MFOSM reduces equation (1) above to give

$$f(X) = f(X^m) + \sum_{i=1}^{n} (x_i - x_i^m)\left(\frac{\partial f}{\partial x_i}\right)_{X^m} \quad \text{.......... (2)}$$

where X^m is the x_i vector evaluated at its mean. From equation (2), it can be derived the function's expected mean and variance to be

$$E[f(X)] \approx f(X^m) \quad \text{.......... (3)}$$

$$\text{var}[f(X)] \approx \sum_{i=1}^{n}\sum_{h=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)_{X^m}\left(\frac{\partial f}{\partial x_h}\right)_{X^m} \text{cov}(x_i, x_h) \quad \text{.......... (4)}$$

Consider now the linear water quality model below. Equation (5) gives the dissolved oxygen (DO) concentration at a particular point j along a river.

$$f(X) = DO_j = B_j + \sum_{i}^{I} W_i a_{ij} \quad \text{.......... (5)}$$

where DO_j is the DO concentration at point j along the river, W_i is the Biochemical Oxygen Demand (BOD) discharge rate of discharger i, B_j is the DO concentration when W_i is zero, a_{ij} is a negative coefficient relating W_i to the loss of DO concentration at point j and I is the total number of dischargers along the river. In this study, B_j and a_{ij} are assumed as stochastic but W_i as deterministic.

Applying MFOSM to the water quality model by substituting equation (5) into equations (3) and (4) gives

$$DO_j^m = B_j^m + \sum_{i}^{I} W_i a_{ij}^m \quad \text{.......... (6)}$$

$$\text{var}[DO_j] = \sum_{i=1}^{I}\sum_{h=1}^{I} W_i W_h \text{cov}(a_{ij}, a_{hj}) + 2\sum_{i=1}^{I} W_i \text{cov}(a_{ij}, B_j) + \text{var}(B_j) \quad \text{.......... (7)}$$

where h is a general counting index, DO_j^m is the DO_j mean, B_j^m is the B_j mean and a_{ij}^m is the a_{ij} mean. The system's uncertainty can thus be expressed in terms of a reliability index dependent on the DO mean and variance. Let β_j be that index for a particular location j.

$$\beta_j = \frac{DO_j^m - DO_j^{std}}{\sigma_{DO_j}} = \frac{B_j^m + \sum_{i}^{I} W_i a_{ij}^m - DO_j^{std}}{\sqrt{\sum_{i=1}^{I}\sum_{h=1}^{I} W_i W_h \text{cov}(a_{ij}, a_{hj}) + 2\sum_{i=1}^{I} W_i \text{cov}(a_{ij}, B_j) + \text{var}(B_j)}} \quad \text{.......... (8)}$$

where DO_j^{std} is the pre-set DO concentration standard to be maintained at point j and σ_{DOj} is the DO_j standard deviation. By assuming that the central limit theorem applies so that DO_j is normally distributed, an assumption that is justified f I is sufficiently large, the reliability of the DO concentration meeting a certain pre-set standard at a location j can be found as

$$\text{reliability} = P\left(DO_j - DO_j^{std} \geq 0\right) = \phi\left(\beta_j\right) \quad \text{.......... (9)}$$

where $\phi(\beta_j)$ is a function that returns the standardized normal cumulative distribution for a specified value of β_j. The greater is β_j, the higher is the reliability of the system. Positive values of β_j give reliabilities greater than 50% while negative values of β_j give reliabilities smaller than 50%.

3.2 MFOSM Applied to Permit Trading

When trading takes place, the discharge locations corresponding to the permits being traded are changed. For systems where locational effects are non-negligible, this modifies a location's β_j value and hence, its reliability. Generally, that change in β_j can be expressed as

$$\Delta\beta_j = \beta_{j,new} - \beta_{j,old} = \left[\frac{DO_j^m - DO_j^{std}}{\sigma_{DO_j}}\right]_{new} - \left[\frac{DO_j^m - DO_j^{std}}{\sigma_{DO_j}}\right]_{old} \quad \text{.......... (10)}$$

where the subscript *old* represents the system at its original state before trading, and the subscript *new* the changed state of the system after trading. Therefore, $\beta_{j,old}$ is location *j*'s reliability index before trading, and $\beta_{j,new}$ is location *j*'s reliability index after trading. From equation (10), it can be deduced that any change in DO reliability due to trading would be dependent on the change in the mean, as well as that in the standard deviation, of the DO distribution. The desired DO standard to be achieved is also a contributing factor. An increase in the mean DO tends to be favorable as it leads to an overall increase in the reliability, but a corresponding increase in the standard deviation could override that increase in the mean, resulting in a worse reliability.

For a clearer idea of how the DO mean and standard deviation might change to produce an overall increase in reliability, equation (10) can be re-written as

$$\Delta\beta_j = \left(F_j - 1\right)\beta_{j,old} \text{ when } \beta_{j,old} \neq 0 \quad \text{.......... (11)}$$

where

$$F_j = \frac{\beta_{j,new}}{\beta_{j,old}} = \frac{\left[DO_j^m - DO_j^{std}\right]_{new}}{\left[DO_j^m - DO_j^{std}\right]_{old}} \times \frac{\left[\sigma_{DO_j}\right]_{old}}{\left[\sigma_{DO_j}\right]_{new}} = \frac{f_{1,j}}{f_{2,j}} \quad \text{.......... (12)}$$

Note that equation (12) defines

$$f_{1,j} = \frac{\left\lfloor DO_j^m - DO_j^{std} \right\rfloor_{new}}{\left\lfloor DO_j^m - DO_j^{std} \right\rfloor_{old}} \qquad \text{and} \qquad f_{2,j} = \frac{\left\lfloor \sigma_{DO_j} \right\rfloor_{new}}{\left\lfloor \sigma_{DO_j} \right\rfloor_{old}} \quad \text{.........} \ (13)$$

Equation (11) above applies to cases where $\beta_{j,old}$ is non-zero. For such cases, it can thus be observed that it is the F_j ratio, not the absolute increase or decrease in the DO mean and/or standard deviation, that determines whether or not a given change in the system produces a positive change in the reliability. When $\beta_{j,old}$ is negative, which is the case when $[DO_j^m\text{-}DO_j^{std}]_{old}$ is negative, only F_j values that are less than unity will yield an increase in the reliability. Conversely, when $\beta_{j,old}$ is positive, which is the case when $[DO_j^m\text{-}DO_j^{std}]_{old}$ is positive, only F_j values that are greater than unity will yield an increase in the reliability. When F_j is exactly one, the reliability remains as before, even though the DO mean and standard deviation might have changed.

For cases where $\beta_{j,old}$ is zero, equation (10) reduces to simply

$$\Delta\beta_j = \beta_{j,new} = \left[\frac{DO_j^m - DO_j^{std}}{\sigma_{DO_j}}\right]_{new} \quad \text{when } \beta_{j,old} = 0 \quad \text{.........} \ (14)$$

$\beta_{j,old}$ is zero when $[DO_j^m\text{-}DO_j^{std}]_{old}$ equals zero. When this is true, the initial reliability is exactly 50%, and the initial DO standard deviation becomes irrelevant. Whether a given change to the system will produce a positive or negative $\Delta\beta_j$ depends only on $[DO_j^m\text{-}DO_j^{std}]_{new}$. A positive $[DO_j^m\text{-}DO_j^{std}]_{new}$ is desirable as it produces a positive $\Delta\beta_j$. The new σ_{DOj} comes into play only when calculating for the extent to which the reliability increases or decreases. It is advantageous for the new σ_{DOj} to be large when $[DO_j^m\text{-}DO_j^{std}]_{new}$ is negative, but small when $[DO_j^m\text{-}DO_j^{std}]_{new}$ is positive.

For further illustration of the principles introduced above, consider the following three scenarios.

I. $[DO_j^m\text{-}DO_j^{std}]_{old}$ is positive and therefore $\beta_{j,old}$ is positive.

II. $[DO_j^m\text{-}DO_j^{std}]_{old}$ is negative and therefore $\beta_{j,old}$ is negative.

III. $[DO_j^m\text{-}DO_j^{std}]_{old}$ is zero and therefore $\beta_{j,old}$ is zero.

Scenario I: When $[DO_j^m\text{-}DO_j^{std}]_{old}$ and hence, $\beta_{j,old}$ are positive, according to equation (11), a F_j ratio that is greater than one is required if it is desired an increase in the reliability. Such a value of F_j will be achieved if and only if $f_{1,j}$ is greater than $f_{2,j}$. The general idea is that an increase in the mean, though encouraging, will not lead to an overall increase in the reliability if there is a too-large increase in the standard deviation. A too-large increase in the standard deviation will offset whatever improvement in the reliability due to the increased mean. Refer to Figure 1 below for a graphical illustration of this notion. Similarly, a reduced mean, though discouraging, is not necessarily harmful if its negative effects are compensated by the positive effects of a sufficiently reduced standard deviation. Refer to Figure 2 below. Furthermore, $f_{1,j}$ must always be positive (i.e. the DO mean must always be greater than the DO standard) for there to be any improvement in the reliability. Due to $f_{2,j}$ being inherently positive, a negative $f_{1,j}$ will give a negative $\Delta\beta_j$ regardless of what $f_{2,j}$ may be.

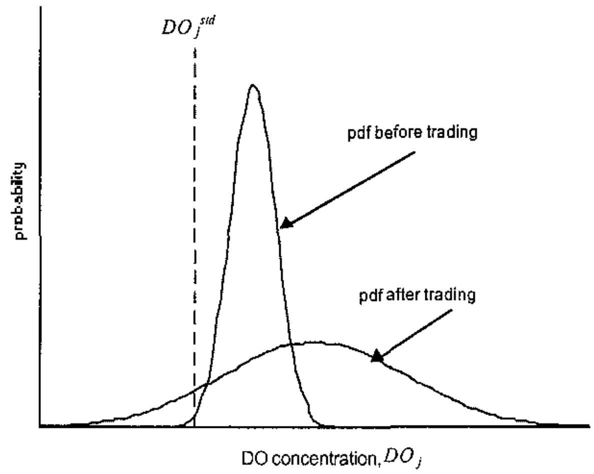

Figure 1: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is positive. Although there is an increase in the mean ($f_{1,j}$>1), due to an increase in the standard deviation ($f_{2,j}$>1) such that $f_{2,j} > f_{1,j}$, there is an overall decrease in the reliability. F_j is greater than zero but less than one.

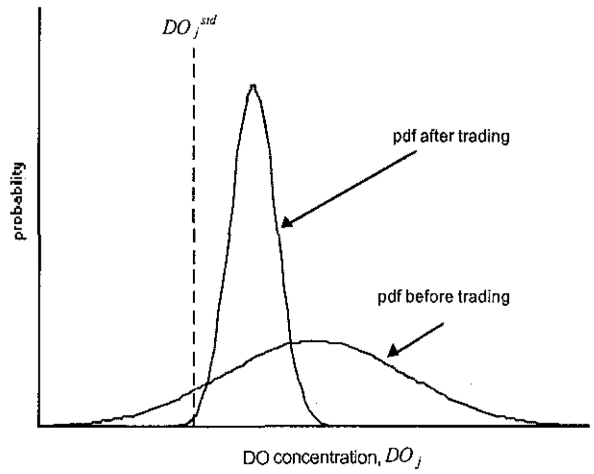

Figure 2: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is positive. Although there is a decrease in the mean (0<$f_{1,j}$<1), due to a decrease in the standard deviation ($f_{2,j}$<1) such that $f_{1,j} > f_{2,j}$, there is an overall increase in the reliability. F_j is greater than one.

Scenario II: When $[DO_j^m - DO_j^{std}]_{old}$ and hence, $\beta_{j,old}$ are negative, it is only when F_j is less than one that an increase in the reliability is possible. For F_j to be less than one, $f_{2,j}$ must be greater than $f_{1,j}$, which can be either positive or negative. A positive $f_{1,j}$ that is greater than unity means a deterioration in the mean DO. When $f_{1,j}$ is positive, a negative $\Delta\beta_j$ may be avoided if the deterioration in the mean is accompanied by an increase in the standard deviation to a new value that is at least $f_{1,j}$ times the original value. Refer to Figure 3 below. On the other hand, $f_{1,j}$ ratios that are less than unity, including those in the negative range, indicate an improvement in the mean. Generally, this leads to a healthier reliability. However, for cases where $f_{1,j}$ is non-negative, but still less than unity, should this increase in the mean be followed by a decrease in the standard deviation such that $f_{2,j}$ becomes smaller than $f_{1,j}$, then the good effects of the improved mean is cancelled, and sometimes even surpassed, by the unpleasant effects of the narrowed standard deviation. Refer to Figure 4 below.

Scenario III: When $[DO_j^m - DO_j^{std}]_{old}$ and $\beta_{j,old}$ are zero, the original reliability before trading is exactly 50% irrespective of the standard deviation. The only requirement for a better after-trading reliability is an increased mean DO such that the new DO_j^m is greater than DO_j^{std}. As for the standard deviation, there is no specific constraint on it as long as there is an increase in the mean. When this is the case, the reliability will be greater than 50% no matter the standard deviation, though a reduced standard deviation is favored. Refer to Figure 5 below. On the contrary, when the mean is decreased to less than DO_j^{std}, the reliability will be less than 50%. For such cases, an increased standard deviation is favored. Refer to Figure 6 below. An unchanged mean means an unchanged reliability regardless of how the standard deviation might change. Refer to Figure 7 below.

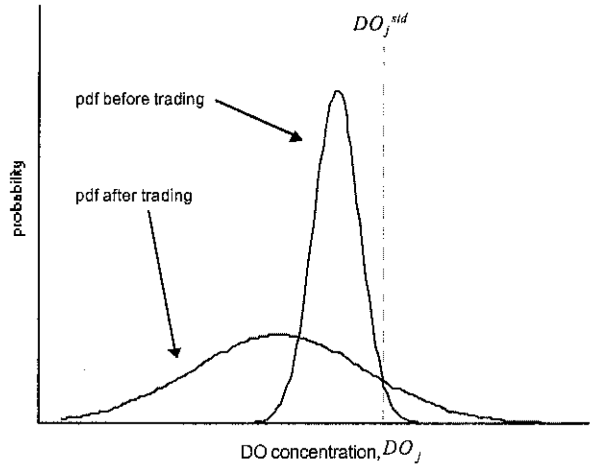

Figure 3: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is negative. Although there is a decrease in the mean ($f_{1,j}$>1), due to an increase in the standard deviation ($f_{2,j}$>1) such that $f_{2,j}$> $f_{1,j}$, there is an overall increase in the reliability. F_j is less than one.

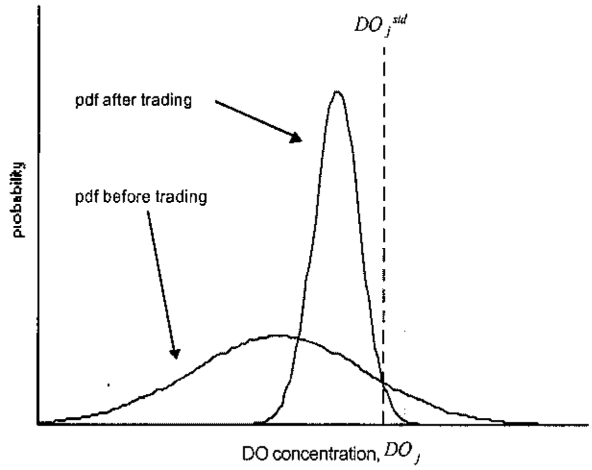

Figure 4: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is negative. Although there is an increase in the mean ($f_{1,j}$<1), due to a decrease in the standard deviation ($f_{2,j}$<1) such that $f_{1,j}$> $f_{2,j}$, there is an overall decrease in the reliability. F_j is greater than one.

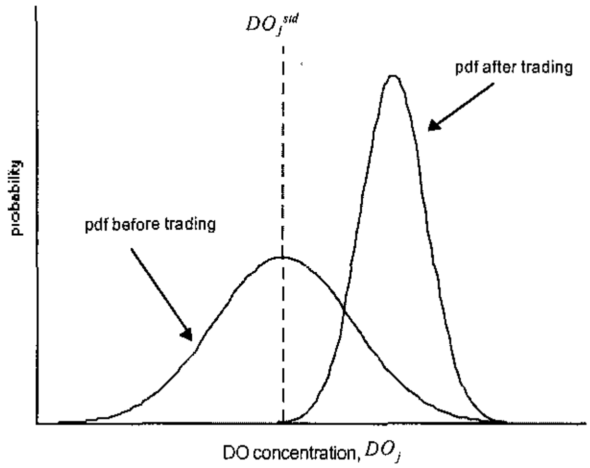

Figure 5: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is zero. A decreased standard deviation is favorable when there is an increased mean. On the overall, there is an increase in the reliability.

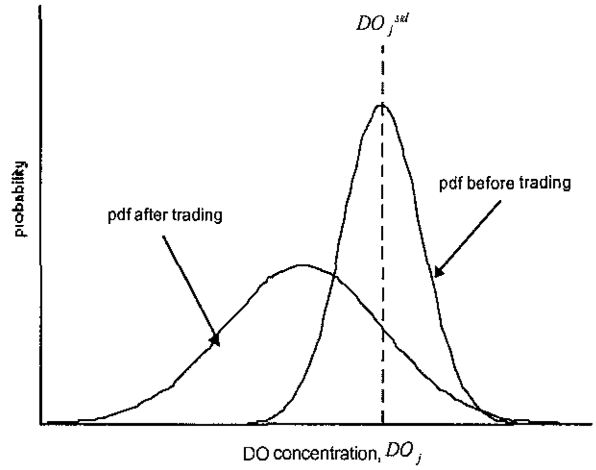

Figure 6: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is zero. An increased standard deviation is favorable when there is a decreased mean. On the overall, there is a decrease in the reliability.

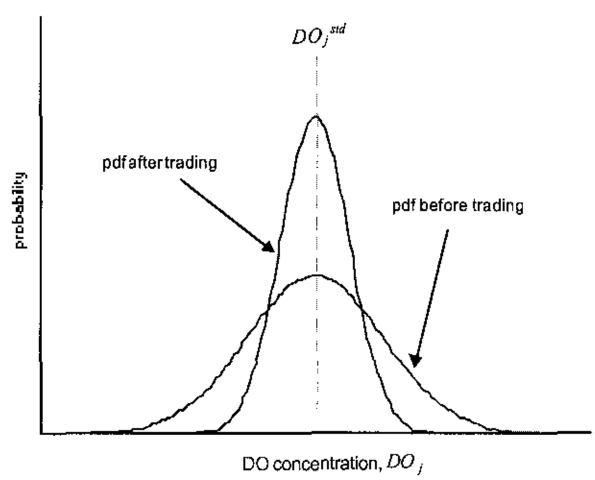

Figure 7: One possible effect of trading on the DO distribution when $\beta_{j,old}$ is zero. The standard is irrelevant when the mean is unchanged. Regardless the standard deviation, the reliability remains exactly 50% when there is no change to the mean.

Since the DO reliability directly relies on its mean and standard deviation, the more fundamental question is what are the factors, within the permit trading context, affecting the mean and standard deviation. For a river system, if defining T_i as the net amount of permits traded by discharger i, equations (6) and (7) can be re-written to give

$$DO^{m}_{j,new} = B^{m}_{j} + \sum_{i}^{ND}\left(W_{i,old} + T_i\right)a^{m}_{ij} \quad \text{.........} (15)$$

$$\operatorname{var}\left(DO_{j,new}\right) = \sum_{i=1}^{ND}\sum_{k=1}^{ND}\left(W_{i,old} + T_i\right)\left(W_{k,old} + T_k\right)\operatorname{cov}\left(a_{ij}, a_{kj}\right)$$

$$+ 2\sum_{i=1}^{ND}\left(W_{i,old} + T_i\right)\operatorname{cov}\left(a_{ij}, B_j\right) + \operatorname{var}\left(B_j\right) \text{.........} (16)$$

$DO^{m}_{j,new}$ is the new mean DO concentration at point j after trading, $\operatorname{var}(DO_{j,new})$ is the new DO variance at point j after trading and $W_{i,old}$ is discharger i's original discharge rate before trading. T_i can be either positive or negative. T_i is positive when there is a net buying of permits by discharger i, and negative when there is a net selling of permits by discharger i. Since the total amount of permits is fixed, the net sum of all permits traded must be zero.

$$\sum_{i=1}^{ND} T_i = 0 \quad \text{.........} (17)$$

From equations (15) and (16), it can be seen that the DO mean and standard deviation are functions of the B_j and a_{ij} distributions, as well as the sign and quantity of T_i. The B_j and a_{ij} distributions in turn, are subject to local weather fluctuations and other similar factors, while T_i is constrained by economic considerations. For further illustration, for a two-discharger system where $T_1=-T_2$, equation (15) can be rearranged to give

$$\Delta DO^{m}_{j} = DO^{m}_{j,new} - DO^{m}_{j,old} = T_1\left(a^{m}_{1j} - a^{m}_{2j}\right) \quad \text{.........} (18)$$

where ΔDO_j^m is the effect of trading on the DO mean concentration at point j, and $DO^{m}_{j,old}$ is the original DO mean at point j before trading. Equation (18) indicates that a trade that transfers permits from a source with a greater negative mean a_{ij} to another with a smaller negative mean a_{ij} brings about an improved DO mean. Refer to Figure 8 below. Figure 8 shows the $\Delta DO_j^m = 0$ line, which overlies the $a_{1j}^m = a_{2j}^m$ line. When T_1 is positive, i.e., when there is a net transfer of permits from discharger 2 to discharger

1, any combination of a_{1j}^{m} and a_{2j}^{m} that falls above the ΔDO_j^m=0 line will cause an increase in the DO mean, and vice versa. The DO mean is independent of trading for $a^m{}_{1j}$ - $a^m{}_{2j}$ combinations that fall on the ΔDO_j^m=0 line. The farther a system's $a^m{}_{1j}$ -$a^m{}_{2j}$ combination is from the ΔDO_j^m=0 line, the more sensitive is the system to trading. Note that the B_j distribution does not affect ΔDO_j^m.

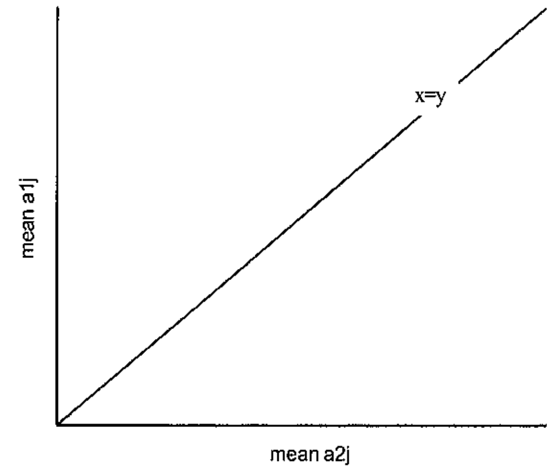

Figure 8: The ΔDO_j^m=0 line for a two-discharger river system. The ΔDO_j^m=0 line is independent of $W_{i,old}$, T_i and the B_j distribution. It overlies the x=y line.

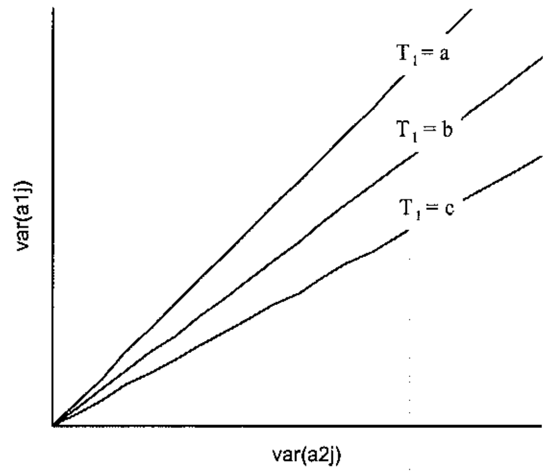

Figure 9: The $\Delta \mathrm{var}(DO_j)$=0 line for a two-discharger river system for a given combination of $W_{i,old}$ and var(B_j). The $\Delta \mathrm{var}(DO_j)$=0 line changes with T_i. Note that $0<a<b<c$.

In much the same way as equation (15) can be re-written to give equation (18), equation (16) can be re-written to give

$$\Delta \operatorname{var}(DO_j) = \operatorname{var}(DO_{j,new}) - \operatorname{var}(DO_{j,old}) = T_1^2\{\operatorname{var}(a_{1j}) - 2\operatorname{cov}(a_{1j}, a_{2j}) + \operatorname{var}(a_{2j})\} + 2T_1\{W_{1,old}\operatorname{var}(a_{1j}) + (W_{2,old} - W_{1,old})\operatorname{cov}(a_{1j}, a_{2j}) - W_{2,old}\operatorname{var}(a_{2j}) + \operatorname{cov}(a_{1j}, B_j) - \operatorname{cov}(a_{2j}, B_j)\} \quad \text{......... (19)}$$

where $\Delta \mathrm{var}(DO_j)$ represents the effect of trading on the DO variance/standard deviation, while $\mathrm{var}(DO_{j,old})$ is the original DO variance at point j before trading. Equation (19) indicates that generally, there will be an increase in the DO variance whenever there is a transfer of permits from a source with a smaller a_{ij} variance to another with a greater a_{ij} variance. However, this is not always the case. The opposite may be true depending on $W_{i,old}$, which represents the initial allocation of permits, and T_l. $\Delta\text{var}(DO_j)$ is also affected by the B_j distribution. Refer to Figure 9 above, which gives the $\Delta\text{var}(DO_j)$=0 line and demonstrates how it changes as T_l changes when all other factors are kept constant. For a given (positive) value of T_l, $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ combinations that fall above its corresponding $\Delta\text{var}(DO_j)$=0 line will cause $\text{var}(DO_j)$ to be increase. In the same way, $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ combinations that fall below the corresponding $\Delta\text{var}(DO_j)$=0 line will cause $\text{var}(DO_j)$ to decrease, and those that fall exactly on the corresponding $\Delta\text{var}(DO_j)$=0 will render the system insensitive to trading. Systems with $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ combinations that lie farther from the $\Delta\text{var}(DO_j)$=0 line tend to be more vulnerable to trading than others with $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ combinations that lie nearer to the $\Delta\text{var}(DO_j)$=0 line. Note that the $\Delta\text{var}(DO_j)$=0 line does not overlap the $\text{var}(a_{1j})$=$\text{var}(a_{2j})$ line.

3.3 A Hypothetical Example of a River System with Two Dischargers

For some numerical confirmation of the ideas developed in the previous sub-sections, consider a hypothetical example of permit trading applied to a stochastic river system with two dischargers. First consider a scenario where $W_{1,old}$ = 5 [M/T], $W_{2,old}$ = 4 [M/T], $a^m{}_{1j}$ = -0.2 [(M/L^3) / (M/T)], $a^m{}_{2j}$ = -0.4 [M/L^3 per M/T], $B^m{}_j$ = 8.0 [M/L^3], $\text{var}(a_{1j})$ = 0.025 [(M/L^3) / (M/T)]^2, $\text{var}(a_{2j})$ = 0.04 [(M/L^3) / (M/T)]^2, $\text{var}(B_j)$ = 0.02 [M/L^3]^2, $\text{cov}(a_{1j},a_{2j})$ = 0.013 [(M/L^3) / (M/T)]^2, $\text{cov}(a_{1j},B_j)$ = 0.009 [(M^2/L^6) / (M/T)] and $\text{cov}(a_{1j},B_j)$ = 0.011 [(M^2/L^6) / (M/T)]. This scenario corresponds to Scenario I as defined in the previous sub-section where for a DO_j^{std} value of 5 [M/L^3], β_{old} is positive.

Consider also a second scenario where $W_{1,old}$ = 5 [M/T], $W_{2,old}$ = 4 [M/T], $a^m{}_{1j}$ = -0.30 [(M/L^3) / (M/T)], $a^m{}_{2j}$ = -0.35 [(M/L^3) / (M/T)], $B^m{}_j$ = 7.0 [M/L^3], $\text{var}(a_{1j})$ = 0.01 [(M/L^3) / (M/T)]^2, $\text{var}(a_{2j})$ = 0.10 [(M/L^3) / (M/T)]^2, $\text{var}(B_j)$ = 0.02 [M/L^3]^2, $\text{cov}(a_{1j},a_{2j})$ = 0.013 [(M/L^3) / (M/T)]^2, $\text{cov}(a_{1j},B_j)$ = 0.006 [(M^2/L^6) / (M/T)] and $\text{cov}(a_{1j},B_j)$ = 0.018 [(M^2/L^6) / (M/T)]. This scenario corresponds to Scenario II as defined in the previous sub-section where for a DO_j^{std} value of 5 [M/L^3], β_{old} is negative.

For both scenarios, refer to Table 1 below for the initial DO mean, standard deviation and reliability before any trading is allowed. Refer also the Figures 10 to 13 to observe how trading might affect the DO mean, standard deviation and reliability. The figures were plotted based on equations (8), (9), (14) and (15). For additional exemplification, four sub-scenarios were defined. Sub-Scenario A is defined as when T_l = -4 [M/T], Sub-Scenario B as when T_l = -2 [M/T], Sub-Scenario C as when T_l = 2 [M/T] and Sub-Scenario D as when T_l = 4 [M/T]. Recall that when T_l is negative, as in the cases of Sub-Scenarios A and B, there is a net transfer of permits from discharger 1 to discharger 2. And when T_l is positive, as in the cases of

Sub-Scenarios C and D, there is a net transfer of permits from discharger 2 to discharger 1. For each of the two scenarios and each of the four sub-scenarios, $\Delta\beta_j$ was calculated. The $f_{1,j}$, $f_{2,j}$ and F_j ratios (refer to equations (12) and (13)) were also determined to verify the concepts proposed in the previous sub-section. Refer to Table 2 below. Moreover, the $\Delta var(DO_j)$=0 and ΔDO_j^m=0 lines were drawn to give further insight to the problem. Refer to Figures 14 and 15.

Table 1: The initial DO mean, standard deviation and reliability (T_l = 0) for Scenarios I and II.

Scenario		I ($\beta_{j,old} > 0$)	II ($\beta_{j,old} < 0$)
$\beta_{j,old}$	[-]	0.285	-0.561
$DO^m_{j,old}$	[M/L^3]	5.400	4.100
$\sigma_{DOj,old}$	[M/L^3]	1.404	1.605

Table 2: Effect of trading on the DO mean, standard deviation and reliability for Sub-Scenarios A to D.

Sub-Scenario		I-A	I-B	I-C	I-D	II-A	II-B	II-C	II-D
T_l	[M/T]	-4.00	-2.00	2.00	4.00	-4.00	-2.00	2.00	4.00
$\Delta\beta_j$	[-]	-0.516	-0.285	0.291	0.523	0.143	0.085	-0.112	-0.164
ΔDO_j^m	[M/L^3]	-0.800	-0.400	0.400	0.800	-0.200	-0.100	0.100	0.200
$\Delta\sigma_{DOj}$	[M/L^3]	0.330	0.122	-0.015	0.081	1.028	0.496	-0.415	-0.640
$f_{1,j}$	[-]	-1.000	0.000	2.000	3.000	1.222	1.111	0.889	0.778
$f_{2,j}$	[-]	1.235	1.087	0.989	1.058	1.640	1.309	0.741	0.601
F_j	[-]	-0.810	0.000	2.021	2.836	0.745	0.849	1.199	1.293

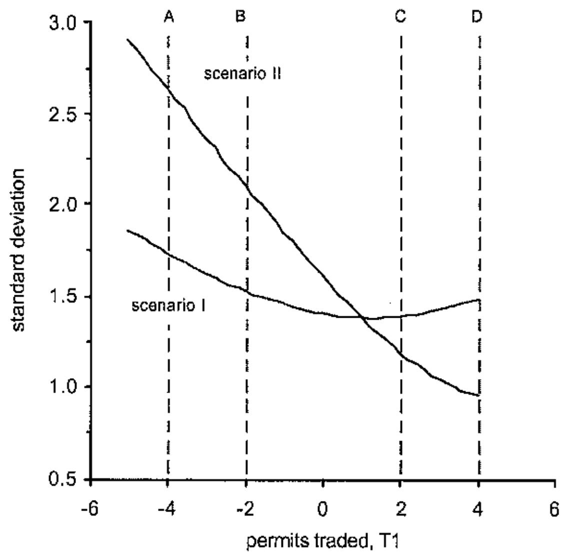

Figure 10: The effect of trading on the DO standard deviation for Scenarios I and II.

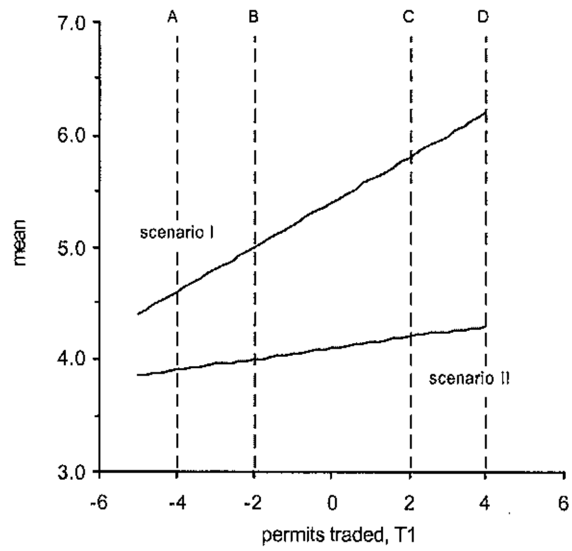

Figure 11: The effect of trading on the DO mean for Scenarios I and II.

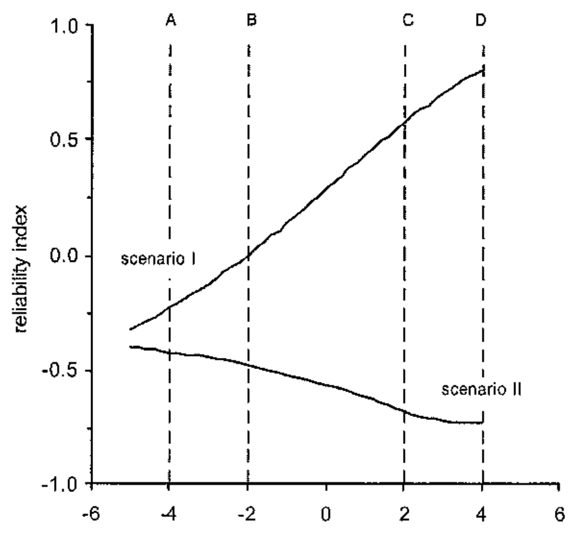

Figure 12: The effect of trading on the DO reliability index, β_j for Scenarios I and II.

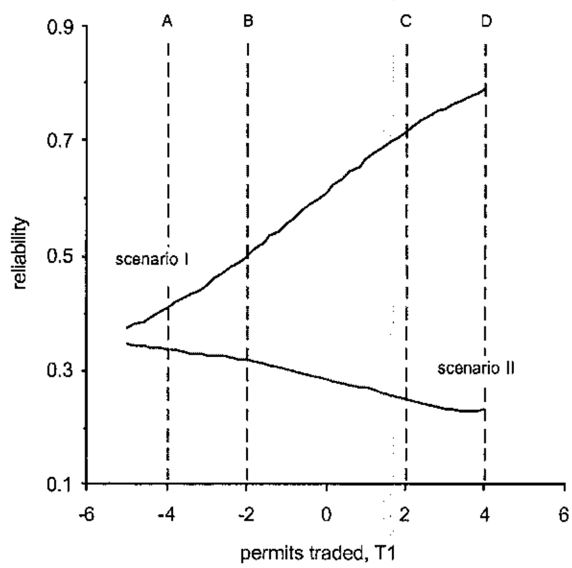

Figure 13: The effect of trading on the DO reliability for Scenarios I and II.

The results presented in Table 2 illustrate the idea proposed in the previous sub-section of how the effect of trading on environmental reliability might be described in terms of certain ratios, namely the $f_{1,j}$, $f_{2,j}$ and F_j ratios. And of how these ratios are able to give a good understanding of how trading-induced changes in the DO mean and/or standard deviation might cause the DO reliability to either increase for the better or decrease for the worse.

Consider first the case where $\beta_{j,old}$ is greater than zero, which is the case of Scenario I and its four sub-scenarios, I-A to I-D. The numbers in Table 2 validate equation (11) that prescribes that for a positive $\beta_{j,old}$ value, a F_j ratio that is greater than unity is required for an increased reliability. Sub-Scenarios I-A and I-B have F_j ratios less than one with negative changes to their reliabilities; while Sub-Scenarios I-C and I-D have F_j ratios greater than one with positive changes to their reliabilities. Furthermore, the system specifications are such that the reliability is a stronger function of the mean, than it is of the standard deviation. Since the standard deviation does not change significantly with trading, an increased mean tends to bring about an increased reliability, and vice versa. Take for example Sub-Scenario I-D where there is an increase in the mean ($f_{1,j}$>1) that helps the reliability. However, at the same time, there is also an increase in the standard deviation ($f_{2,j}$>1) that inhibits the reliability. Since $f_{1,j}$ is greater than $f_{2,j}$, which means that the positive effects of the increased mean outweighs the negative effects of the increased standard deviation, there is an overall increase in the reliability (F_j>1). Take also the example of Sub-Scenario I-A where trading has caused the mean to fall to below DO_j^{std} ($f_{1,j}$<0) and by that alone, the reliability to drop (F_j<0<1). This is regardless of the changes to the standard deviation, which incidentally, has increased. However, the increase in the standard deviation ($f_{2,j}$>1) does mitigate the negative effects of the decreased mean, even though it is unable to fully offset them.

Consider now the case where $\beta_{j,old}$ is smaller than zero, which is the case of Scenario II and its four sub-scenarios, II-A to II-D. For this scenario, F_j ratios smaller than unity are desired, as they bring about better reliabilities (equation (11)). Again, the results in Table 1 confirm this. Sub-Scenarios II-A and II-B have F_j ratios that are less than one, and reliabilities that are improved by trading. On the other hand, Sub-Scenarios II-C and II-D have F_j ratios that are greater than one, but reliabilities that are made worse by trading. Unlike Scenario I, Scenario II's specifications are such that the reliability is no more sensitive to changes in the mean than to changes in the standard deviation. For instance, Sub-Scenario II-A has a reduced mean $f_{1,j}$>1) but an improved reliability (F_j<1). This is due to its increased standard deviation ($f_{2,j}$>1) being able to counterbalance the effects of the decreased mean ($f_{2,j}$> $f_{1,j}$). In the same manner, Sub-Scenario II-C has an improved mean $f_{1,j}$<1) but a reduced reliability (F_j>1). And in the same way, this is due to its decreased standard deviation ($f_{2,j}$<1) neutralizing the good effects of the increased mean ($f_{2,j}$< $f_{1,j}$).

The two scenarios can also be described graphically in relation to their $\Delta\text{var}(DO_j)$=0 and ΔDO_j^m=0 lines. Refer to Figures 14 and 15 below. Figure 14 shows the a^m_{1j} - a^m_{2j} points for Scenarios I (denoted as SI) and II (denoted as SII). The a^m_{1j} - a^m_{2j} points for both scenarios fall above the ΔDO_j^m=0 line and because of this, the DO mean increases whenever T_l is positive (as it is for Sub-Scenarios I-C, I-D, II-C and II-D), and decreases whenever T_l is negative (as it is for Sub-Scenarios I-A, I-B, II-A and II-B). The SI point lies farther from the ΔDO_j^m=0 line than does the SII point. This explains why the reliability is so much more sensitive to changes in the mean in Scenario I than in Scenario II.

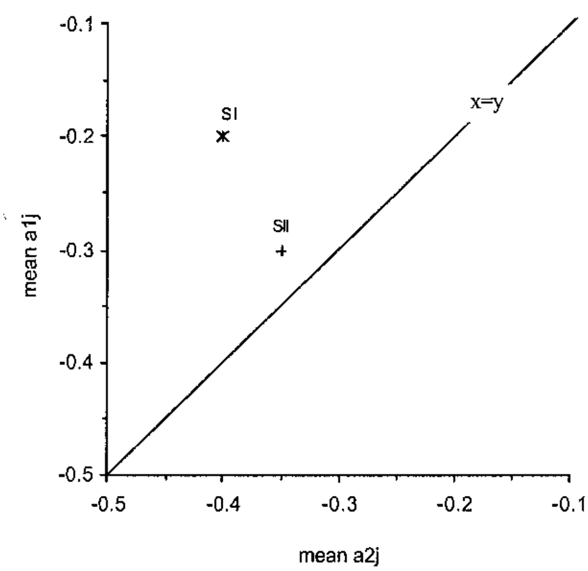

Figure 14: The effect of trading on the DO reliability index, β_j for Scenarios I and II.

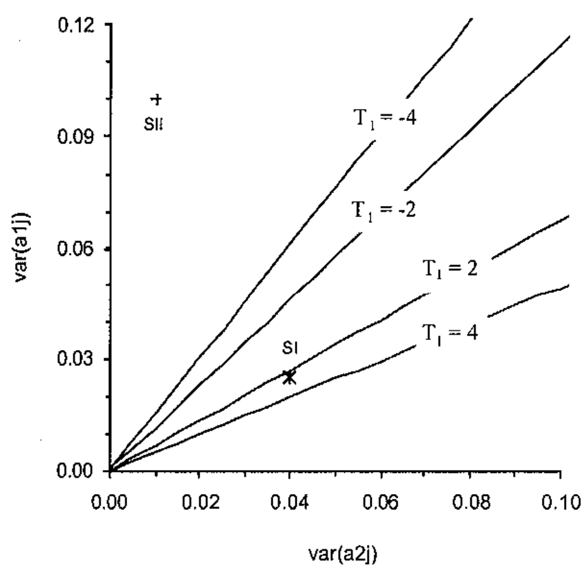

Figure 15: The effect of trading on the DO reliability for Scenarios I and II.

Figure 15 shows the $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ points for both scenarios. Again, the point for Scenario I is denoted as SI while the point for Scenario II is denoted as SII. Note that the SI point falls below the $\Delta\text{var}(DO_j)$=0 line for T_l equal to –4[M/T], –2[M/T] and 2[M/T], but above the $\Delta\text{var}(DO_j)$=0 line for T_l equal to 4[M/T]. This corresponds to the results in Table 2 that shows that the standard deviation increases with trading for Sub-Scenarios I-A, I-B and I-D, but decreases with trading for Sub-Scenario I-C. This proves the point put forth in the previous sub-section of how $\text{var}(a_{1j})$-$\text{var}(a_{2j})$ combinations that fall below the $\Delta\text{var}(DO_j)$=0 line will cause the standard deviation to decrease with trading when T_l is positive, or to increase with trading when T_l is negative. The data for Scenario II further support this argument. The SII point falls above the $\Delta\text{var}(DO_j)$=0 line for all four trading possibilities, which fully agrees with the observation that the standard deviation increases for the sub-scenarios where T_I is positive (Sub-Scenarios II-C and II-D), but decreases for the sub-scenarios where T_I is negative (Sub-Scenarios II-A and II-B). It is also interesting to note that the SII point is farther away from the $\Delta\text{var}(DO_j)$=0 line than is the SI point. This explains why changes in the standard deviation are more able to override the effects of changes in the mean for Scenario II, than for Scenario I.

4.0 METHODOLOGY

One of the objectives of this study is better to understand how discharge permit trading might affect the mean and variation of environmental quality. To demonstrate the methods developed, two riverine systems are analyzed. The first is the Willamette River in Oregon, USA and the second is the Athabasca River in Alberta, Canada.

The Willamette River is approximately 300 km long, with a drainage basin of around 29785 km^2 in area. Bounded by the Coast and Cascade mountain ranges, its mainstem flows in a northerly direction before discharging into the Columbia River just downstream of Portland. Not only is the Willamette River popular for fishing and recreation, it is also a key drinking water source for numerous communities alongside it. There are over fifty municipal and industrial facilities [Tetra Tech, 1995] discharging into the river. This study assumes seventeen of these dischargers, comprised of eleven municipal Wastewater Treatment Plants (WWTP) and six Pulp and Paper Mills (PPM), as controlled sources, and the remaining as uncontrolled sources.

The Athabasca River begins in the Columbia Ice Field glacier in the Canadian Rockies, and is the longest river in Alberta. It measures 1538 km in length from its origin at the Columbia Icefield in the Jasper National Park to its mouth at Lake Athabasca in the Wood Buffalo National Park. The Athabasca River is prized for its outstanding natural beauty, historical significance and recreational value. Like most of Northern Alberta, the Athabasca River Basin is largely forested, making it an important source of pulpwood for paper-making. There are nine sizeable point source facilities discharging into the river, mostly PPMs and WWTPs. This study considers five of these facilities, all of which are PPMs, as controlled sources, and the remaining four as uncontrolled sources. Of the five controlled sources, four discharge directly into the Athabasca River and one indirectly via the Lesser Slave River, which is a tributary to the Athabasca River.

Table 3 gives further details of the controlled sources and was compiled from information provided by Tetra Tech [1995] and Tolson [2000], for the Willamette River, and from Macdonald and Hamilton [1989] for the Athabasca River.

Each system is modeled and simulated to predict how it might behave under a Tradable Discharge Permit (TDP) program. For each system, an environmental-response model and a permit-trading model are developed, and by linking the two models together, the system is first optimized to determine its initial permit allocation, then re-optimized to find its final TDP equilibrium. A comparison between a system's environmental quality before and after trading (characterized as the water quality reliability) can then be made. This is so to gain some quantitative measure of how trading might cause the environment to

Table 3: List of controlled point dischargers for the Willamette and Athabasca Rivers.

#	Controlled Point Discharger	Industry (PPM Subtype)	Location (RK)
The Willamette River Case			
1	Metropolitan W/W Management Commission	WWTP	16
2	Pope & Talbot Inc.	PPM (Alkaline-Market)	65
3	James River Paper Co. Inc.	PPM (Deink-Fine & Tissue)	65
4	City of Corvallis	WWTP	91
5	City of Albany	WWTP	111
6	Willamette Industries Inc.	PPM (Alkaline-Unbleached)	115
7	City of Salem	WWTP	176
8	City of Newberg	WWTP	221
9	Smurfit Newsprint Corp. (Newberg)	PPM (Groundwood-Fine)	221
10	City of Wilsonville	WWTP	239
11	City of Canby	WWTP	248
12	Smurfit Newsprint Corp. (Oregon City)	PPM (Deink-Newsprint)	257
13	Simpson Paper Company	PPM (Deink-Fine & Tissue)	259
14	Tri-City Service District	WWTP	261
15	City of Portland	WWTP	269
16	Oak Lodge Sanitary District	WWTP	269
17	Clackamas Co. Service District # 1	WWTP	272
The Athabasca River Case			
1	Welwood of Canada Ltd.	PPM (Alkaline-Market)	14
3	Alberta Newsprint Company	PPM (Nonintegrated Boards)	203
2	Millar Western Pulp Ltd.	PPM (Nonintegrated Boards)	212
4	Alberta Energy Company (AEC)	PPM (Nonintegrated Boards)	498
5	Alberta Pacific Forest Industries Inc.	PPM (Alkaline-Market)	610

Notes:

1. PPM Subtype as defined by E.C. Jordan [1979].
2. RK 0 is defined as the most upstream point of the river being modeled.
3. AEC discharges into the Lesser Slave River, which is a tributary that discharges into the Athabasca River at RK 498.
4. Table compiled from Tetra Tech [1995], Tolson [2000] and Macdonald & Hamilton [1989].

change, and from there to pass judgment on whether or not unrestricted trading is an appropriate means of pollution control.

In this study, environmental quality is measured as the reliability of the DO concentration meeting a certain pre-set standard, where reliability can be defined as the probability of the system performing as desired or better. The DO concentration is an appropriate measure of environmental quality. Prolonged exposure to low DO levels will cause fish stress, if not fish kill. Furthermore, a healthy DO concentration is required to prevent anaerobic conditions that will render the water aesthetically unpleasing. This use of reliability is a parsimonious and environmentally meaningful way of combining concepts of mean and variance of the critical water quality parameter i.e. the DO concentration.

To further limit the scope of this study, only BOD wasteloads are considered regulated and tradable. Nitrogen, phosphorus and other waste discharges are either assumed negligible and not included in the model, as for the Athabasca River case, or kept constant and uninfluenced by trading, as for the Willamette River case.

For details of the computational work involved and the assumptions made, refer to the following sub-sections. Sub-Section 4.1 describes the environmental-response models developed for each river, while Sub-Section 4.2 explains further the permit-trading model.

4.1 Environmental-Response Model

Recall from Section 3.1 that equation (5) gives the DO concentration at a point in a river, and, for stochastic systems, equations (8) and (9) the reliability of the DO concentration meeting a certain pre-set standard. In these equations, DO_j, B_j and a_{ij} are random variables characterized in terms of their means, variances and covariances. Their randomness represents the environment's stochastic nature, particularly, the variation of stream flow and water temperature. W_i is deterministic as it is a function only of human decisions and thus, independent of environmental fluctuations. In this study, DO_j and β are output variables, W_i an input variable and B_j and a_{ij} input parameters. The following sub-sections explain how the B_j and a_{ij} distributions were derived for first the Willamette River case, then the Athabasca River case.

4.1.1 The Willamette River

For the Willamette River case, the B_j and a_{ij} distributions were derived, using Latin Hypercube simulation, from a modification of the Tetra Tech QUAL2EU Willamette River model [Tetra Tech, 1995], with data from Tolson [2000]. For details of the QUAL2EU Water Quality Model, refer to Brown & Barnwell [1987].

The original Tetra Tech QUAL2EU model [Tetra Tech, 1995] is one-dimensional and steady state. It divides the Willamette mainstem into 141 reaches of uniform physical characteristics, with each reach being further divided into 0.161 km long elements. Included in the model are 53 point-source dischargers and 14 tributaries. The model was calibrated using August 1992 data, and verified using August 1994 data. The model was specifically designed for the critical low-flow, high-temperature months of July, August and September. The model is fairly comprehensive. It does not neglect the interdependencies between the nitrogen, phosphorus and algae concentrations, nor their effects on the DO concentration profile. Nevertheless, it is not entirely accurate. It fails to consider the effect of backwater mixing from the Columbia River, which is not insignificant for the portion of the river between Willamette Falls and the river mouth. It also wrongly neglects non-point source discharges.

The original Tetra Tech QUAL2EU model [Tetra Tech, 1995] is deterministic. To meet the purposes of this study, the original model was modified according to suggestions by Tolson [2000]. The input variables for stream flow, temperature and Sediment Oxygen Demand (SOD), originally deterministic constants, were re-entered as random variables, characterized by probability distribution functions, to reflect the stochastic environment. Refer to Table A-1 in Appendix A, which was compiled by Tolson [2000], who estimated the stream flow and temperature probability distribution functions from historical data collected by the United States Geological Society (USGS) (refer to www.usgs.gov), and the SOD probability distribution function from field data by Tetra Tech [1995].

As suggested by Tolson [2000], for the stream flow, only the headwater flows for the Willamette River mainstem and three of its major tributaries i.e. the McKenzie, Santiam and Clackamas Rivers, were made random. The headwater flows for the remaining eleven tributaries were kept deterministic at their August 1992 values. As for the temperature, of which a separate input value is required for each reach, only the input for Reach 81 (at Salem at RK 135) was made random. This is due to the scarcity of historical data. The input temperature values for the other reaches were held deterministic but as functions of the Reach 81 input. For the SOD, which was deemed negligible by Tetra Tech [1995] for portions of the river upstream of RK 81, both SOD input values were randomized. The first SOD input value is for the river section between RK 42 and RK 81, while the second input value is for the river section between the river mouth and RK 42. The SOD was further assumed to be uniform within each section.

Tolson [2000] also suggested changes to the DO reaeration coefficient. The original Tetra Tech [1995] model determines the reaeration coefficient using the O'Connor and Dobbins [1958] equation, which calculates the reaeration coefficient from the average stream velocity and depth. However, the O'Connor and Dobbins [1958] equation does not always give predictions that match reality. The O'Connor and Dobbins [1958] equation in the original model was therefore modified to include an error term. Based on work by Melching and Flores [1999], who developed a database of more than 370 measured reaeration coefficient values, Tolson [2000] proposed that error term be random, and varying according to the probability distribution function given in Table A-1.

Tolson [2000] also determined correlation coefficients between the various random variables (refer to Table A-2 in Appendix A). With the data and suggestions by Tolson [2000] applied, the Tetra Tech [1995] QUAL2EU model was then re-programmed into a spreadsheet.

Table 4: Mean a_{ij} and B_j for the river mouth at RK 300 for Willamette River case

Item	Discharger	Mean for the River Mouth i.e. j = RK 300
a_{1j}	Metropolitan W/W Management Commission	-0.864
a_{2j}	Pope & Talbot Inc.	-0.958
a_{3j}	James River Paper Co. Inc.	-0.958
a_{4j}	City of Corvalis	-1.004
a_{5j}	City of Albany	-1.043
a_{6j}	Willamette Industries Inc.	-1.057
a_{7j}	City of Salem	-1.241
a_{8j}	City of Newberg	-1.307
a_{9j}	Smurfit Newsprint Corp. (Newberg)	-1.307
a_{10j}	City of Wilsonville	-1.343
a_{11j}	City of Canby	-1.377
a_{12j}	Smurfit Newsprint Corp. (Oregon City)	-1.403
a_{13j}	Simpson Paper Company	-1.363
a_{14j}	Tri-City Service District	-1.399
a_{15j}	City of Portland	-1.381
a_{16j}	Oak Lodge Sanitary District	-1.353
a_{17j}	Clackamas Co. Service District # 1	-1.306
B_j	---	6.788

Notes:

1. The a_{ij} means are in the units of (mg/L)/(kg BOD_u/s). The B_j mean is in the units of mg/L.

Table 5: a_{ij}-B_j variance/covariance matrix for the river mouth at RK 300 for the Willamette River.

Item	a_{1j}	a_{2j}	a_{3j}	a_{4j}	a_{5j}	a_{6j}	a_{7j}	a_{8j}	a_{9j}	a_{10j}	a_{11j}	a_{12j}	a_{13j}	a_{14j}	a_{15j}	a_{16j}	a_{17j}	B_j
a_{1j}	0.020	0.022	0.022	0.024	0.025	0.025	0.030	0.031	0.031	0.031	0.031	0.031	0.030	0.030	0.029	0.028	0.027	0.016
a_{2j}	0.022	0.025	0.025	0.027	0.028	0.028	0.034	0.036	0.036	0.035	0.036	0.035	0.034	0.035	0.033	0.033	0.031	0.018
a_{3j}	0.022	0.025	0.025	0.027	0.028	0.028	0.034	0.036	0.036	0.035	0.036	0.035	0.034	0.035	0.033	0.033	0.031	0.018
a_{4j}	0.024	0.027	0.027	0.028	0.030	0.030	0.036	0.038	0.038	0.038	0.038	0.038	0.037	0.038	0.036	0.035	0.033	0.018
a_{5j}	0.025	0.028	0.028	0.030	0.031	0.032	0.038	0.040	0.040	0.040	0.040	0.040	0.039	0.040	0.038	0.037	0.035	0.019
a_{6j}	0.025	0.028	0.028	0.030	0.032	0.032	0.039	0.040	0.040	0.040	0.041	0.041	0.040	0.040	0.039	0.038	0.036	0.019
a_{7j}	0.030	0.034	0.034	0.036	0.038	0.039	0.047	0.049	0.049	0.049	0.050	0.050	0.049	0.050	0.048	0.047	0.045	0.021
a_{8j}	0.031	0.036	0.036	0.038	0.040	0.040	0.049	0.052	0.052	0.052	0.053	0.054	0.052	0.053	0.052	0.051	0.049	0.019
a_{9j}	0.031	0.036	0.036	0.038	0.040	0.040	0.049	0.052	0.052	0.052	0.053	0.054	0.052	0.054	0.052	0.051	0.049	0.019
a_{10j}	0.031	0.035	0.035	0.038	0.040	0.040	0.049	0.052	0.052	0.054	0.055	0.056	0.055	0.056	0.055	0.054	0.052	0.015
a_{11j}	0.031	0.036	0.036	0.038	0.040	0.041	0.050	0.053	0.053	0.055	0.057	0.059	0.057	0.059	0.058	0.056	0.055	0.011
a_{12j}	0.031	0.035	0.035	0.038	0.040	0.041	0.050	0.054	0.054	0.056	0.059	0.061	0.059	0.061	0.060	0.059	0.057	0.007
a_{13j}	0.030	0.034	0.034	0.037	0.039	0.040	0.049	0.052	0.052	0.055	0.057	0.059	0.058	0.060	0.059	0.058	0.056	0.005
a_{14j}	0.030	0.035	0.035	0.038	0.040	0.040	0.050	0.053	0.054	0.056	0.059	0.061	0.060	0.061	0.060	0.059	0.058	0.005
a_{15j}	0.029	0.033	0.033	0.036	0.038	0.039	0.048	0.052	0.052	0.055	0.058	0.060	0.059	0.060	0.060	0.059	0.058	0.001
a_{16j}	0.028	0.033	0.033	0.035	0.037	0.038	0.047	0.051	0.051	0.054	0.056	0.059	0.058	0.059	0.059	0.058	0.057	0.000
a_{17j}	0.027	0.031	0.031	0.033	0.035	0.036	0.045	0.049	0.049	0.052	0.055	0.057	0.056	0.058	0.058	0.057	0.056	-0.002
B_j	0.016	0.018	0.018	0.018	0.019	0.019	0.021	0.019	0.019	0.015	0.011	0.007	0.005	0.005	0.001	0.000	-0.002	0.320

Notes:

1. The i in a_{ij} is the discharger number. The dischargers are numbered according to Tables 3 and 6.

2. The a_{ij}-a_{ij} variances/covariances are in the units of $[(mg/L)/(kg\ BOD_u/s)]^2$. The a_{ij}-B_j covariances are in the units of $(mg/L)^2/(kg\ BOD_u/s)$. The B_j-B_j variance is in the units of $(mg/L)^2$.

Multiple realizations of B_j and a_{ij} were then derived using a Latin Hypercube simulation, with the help of the software @Risk by Palisade (www.palisade.com). The a_{ij} were derived for each of the seventeen controlled sources (refer to Table 3). B_j and a_{ij} were derived for the river mouth, which preliminary studies found to be the system's sole critical point. B_j was derived by setting to zero W_i for all seventeen of the controlled sources. The resulting DO_j gives B_j. a_{ij} for the first discharger was then determined by setting to zero W_i for all but the first of the controlled sources, which was set to a unit discharge amount. The resulting DO_j subtracted by B_j gives a_{ij} for the first discharger. In the same manner, a_{ij} for the subsequent dischargers was found.

The Latin Hypercube simulation was carried out for 5000 iterations to obtain 5000 realizations of B_j and a_{ij}. Based on the 5000 realizations, the B_j and a_{ij} distributions were determined using common statistical methods. Refer to Tables 4 and 5 above for the B_j and a_{ij} means, variances and covariances found. These values were then introduced into equations (5), (8) and (9) to estimate the river's critical DO reliability as a function of W_i.

4.1.2 The Athabasca River

The B_j and a_{ij} distributions for the Athabasca River were derived from the thirty lowest stream flow values for each year from the period 1963-92, the common period for the four principal gauges on the river, Hinton, Whitecourt, Athabasca, and Ft. McMurray [Burn, Personal communication, 1990]. These streamflow data were incorporated into a modified version of the Streeter-Phelps model [Streeter & Phelps, 1925; Chapra, 1997]. The modified model includes the effects of oxygen demanding substances in the sedimentary layer i.e. the Sediment Oxygen Demand (SOD) and is one-dimensional, steady-state and deterministic. The model was based on data and schematics by Macdonald and Hamilton [1989], and was calibrated for the winter period. The Athabasca River is a winter-critical river. Low dilution rates, due to low flows, combined with an almost complete ice-cover, makes the winter period especially vulnerable to BOD discharges and high DO deficits. The model incorporates 25 tributaries, five PPMs, three WWTPs and one oil-processing plant. Note that one of the PPMs, the Alberta Energy Company (AEC), does not discharge directly into the Athabasca mainstem, but into the Lesser Slave River, a tributary. The model covers 1150 km of river, including the Lesser Slave River, with the town of Hinton being the most upstream point of interest. It divides the Athabasca mainstem into 52 reaches, and the Lesser Slave River into 4 reaches, each of uniform physical characteristics.

By partitioning the Streeter-Phelps model into seven BOD compartments (one for each of the five PPMs, one for the three WWTPs and the one oil-processing plant combined, and one for the background BOD) and by running the modified model multiple times, each time with a different set of flow inputs, Eheart [Personal communication, 2002] was able to derive multiple realizations of B_j and a_{ij}. In this model, B_j is defined as the DO concentration when the five PPM wasteloads are set zero but the WWTP and oil-processing plant wasteloads maintained at their original rates given in the Macdonald and Hamilton [1989] report.

In total, Eheart [Personal communication, 2002] obtained thirty realizations of B_j and a_{ij} from thirty years worth of low-flow data. Refer to Table A-3 in Appendix A for the low-flow data. To estimate the stream flow at portions of the river between the gauges, Eheart [Personal communication, 2002] had to pro-rate the measured data according to proportions derived from the 7Q10 flows reported by Macdonald and Hamilton [1989].

The Athabasca River has two critical points, the first at RK 449 corresponding to Reach 27, which is just upstream of the Lesser Slave and Athabasca Rivers confluence, and the second at RK 811 corresponding to Reach 37, which is just upstream of the Grande Rapids. For simplicity sake, this study assumes that the individual reliabilities at the two critical locations are co-dependent such that they tend to vary together so that on the overall, the system reliability equals the reliability at the constraining location. B_j and a_{ij} were found for both critical locations. Refer to Tables A-4 and A-5 in Appendix A for the thirty B_j and a_{ij} realizations obtained.

The B_j and a_{ij} distributions, in terms of their variances, covariances and means, were found from the multiple B_j and a_{ij} realizations, using common statistical methods. Refer to Tables 6 and 7 below for the results obtained, which subsequently were substituted into equations (5), (8) and (9) to determine the critical DO reliabilities subject to W_i.

Table 6: Mean a_{ij} and B_j for the Athabasca River case at RK 449 and RK 811.

Item	Discharger	Mean for Reach 27 i.e. j = RK 449	Mean for Reach 37 i.e. j = RK 811
a_{1j}	Welwood of Canada Ltd.	-0.595	-0.322
a_{2j}	Alberta Newsprint Company	-0.105	-0.058
a_{3j}	Millar Western Pulp Ltd.	-0.479	-0.228
a_{4j}	Alberta Energy Company (AEC)	0.000	-0.093
a_{5j}	Alberta Pacific Forest Industries Inc.	0.000	-0.251
B_j	---	8.514	8.690

Notes:

1. The a_{ij} means are in the units of (mg/L)/(ton BOD_5/d). The B_j mean is in the units of mg/L.

Table 7: The a_{ij}-B_j variance/covariance matrix for RK 449 and RK 811 for the Athabasca River.

Item	a_{1j}	a_{2j}	a_{3j}	a_{4j}	a_{5j}	B_j
j = RK 449 at Reach 27						
a_{1j}	0.0081	0.0007	0.0047	0.0000	0.0000	-0.0122
a_{2j}	0.0007	0.0001	0.0005	0.0000	0.0000	-0.0029
a_{3j}	0.0047	0.0005	0.0033	0.0000	0.0000	-0.0064
a_{4j}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
a_{5j}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B_j	-0.0122	-0.0029	-0.0064	0.0000	0.0000	0.3416
j = RK 811at Reach 37						
a_{1j}	0.0060	0.0009	0.0036	-0.0005	0.0039	0.0034
a_{2j}	0.0009	0.0002	0.0006	-0.0001	0.0006	0.0005
a_{3j}	0.0036	0.0006	0.0024	-0.0003	0.0025	0.0022
a_{4j}	-0.0005	-0.0001	-0.0003	0.0003	-0.0002	-0.0004
a_{5j}	0.0039	0.0006	0.0025	-0.0002	0.0029	0.0026
B_j	0.0034	0.0005	0.0022	-0.0004	0.0026	0.0033

Notes:

1. The i in a_{ij} is the discharger number. The dischargers are numbered according to Tables 3 and 6.
2. The a_{ij}-a_{ij} variances/covariances are in the units of $[(mg/L)/(ton\ BOD_5/d)]^2$. The a_{ij}-B_j covariances are in the the units of $(mg/L)^2/(ton\ BOD_5/d)$. The B_j-B_j variance is in the units of $(mg/L)^2$.

4.2 Permit-Trading Model

The permit-trading model can be divided into two parts, the first to determine the initial permit allocation, and the second to find the final TDP equilibrium. The model requires the input of certain cost data, which were taken from Tolson [2000], who updated figures by Van Note et al [1975] and E.C. Jordan [1979], for the Willamette River; and from Eheart [Personal communication, 2002], who referred to E.C. Jordan [1979], for the Athabasca River. Refer to Tables B-1 to B-17 in Appendix B for the Willamette River cost data, and Tables B-18 to B-22 for the Athabasca River cost data, used in this study. The tables also give the results obtained from the piecewise linearization of the raw data, which was carried out to convert the originally non-convex and discrete cost curves into a more manageable form that is not only convex but also linear.

4.2.1 Initial Permit Allocation Sub-Model

At the onset of a TDP program, the program participants i.e. the controlled point dischargers are allocated a certain amount of permits, each according to some formula that is equitable to all stakeholders involved. In this study, for the Willamette River case, that formula is taken to be a uniform-reduction equation i.e. the initial allocation is based on what the dischargers' wasteloads would be if they were required to reduce their current wasteloads by a certain uniform percentage. As for the Athabasca River case, where all the controlled sources are from the same industry, that formula is taken to be a uniform-production-based equation i.e. the initial allocation is based on what the dischargers' wasteloads would be if they were required to limit their discharges to a certain uniform amount of BOD per unit of paper pulp production.

The initial permit allocation for a system can thus be represented as the solution to the following optimization problem.

$$MIN\ \ Cost = \sum_{i=1}^{I} A_i - \sum_{i=1}^{I}\sum_{k=1}^{K} G_{ik} w_{ik} \quad \text{.......... (20)}$$

Subject to the constraints

$$L_{ik} \le w_{ik} \le U_{ik}, \ \text{ all } i \text{, all } k \quad \text{.......... (21)}$$

$$P\left(DO_j \ge DO_j^{std}\right) = \phi(\beta) \ge \alpha\ ,\ j = \text{all critical points} \quad \text{.......... (22)}$$

$$W_i = \sum_{k=1}^{K} w_{ik} = f(R), \text{ all } i \quad \text{.......... (23)}$$

Where

$$\beta = \frac{DO_j^m - DO_j^{std}}{\sigma_{DO_j}} = \frac{B_j^m + \sum_{i}^{I} W_i a_{ij}^m - DO_j^{std}}{\sqrt{\sum_{i=1}^{I}\sum_{h=1}^{I} W_i W_h \operatorname{cov}\left(a_{ij}, a_{hj}\right) + 2\sum_{i=1}^{I} W_i \operatorname{cov}\left(a_{ij}, B_j\right) + \operatorname{var}\left(B_j\right)}} \quad \text{.......... (8)}$$

A_i is the extrapolated waste abatement cost for discharger i when W_i is zero, w_{ik} is piece k of W_i (W_i is broken into several pieces by the piecewise linearization of the raw cost data), G_{ik} is the gradient for piece k of discharger i's cost curve, L_{ik} is the w_{ik} lower limit, U_{ik} is the w_{ik} upper limit, K is the total number of pieces W_i breaks into, h is a general counting index, $f(R)$ is some function of R, R is a constant determined by α and finally, α is the system's desired critical before-trading reliability.

In the optimization of the above model, w_{ik} are the decision variables. w_{ik} sum over k to give W_i. Note that, in this study, W_i include only the discharge of BOD. The discharges of other pollutants, such as nitrogen and phosphorus, are assumed regulated by other means and thus, for the Willamette River case, maintained constant at their original values given in the Tetra Tech QUAL2EU model [Tetra Tech, 1995], and, for the Athabasca River case, not included in the model. Note also that only the controlled sources (refer to Table 3) are simulated as participating in the TDP program. Therefore, I =17 for the Willamette River case, and I =5 for the Athabasca River case. The discharge rates for the remaining uncontrolled sources, for both BOD and non-BOD, are kept constant and unchanged during the optimization process.

Equation (20) is the objective function, which is to minimize the cost required to achieve a certain level of before-trading reliability. Equations (21) to (23) are the model constraints. Equation (21) bounds W_{ik} to limits determined by the piecewise linearization of discharger i's cost curve. Equation (22) ensures the before-trading water quality is as desired or better. Equation (23) makes certain that W_i are equitable to all stakeholders involved, where equity is defined by the function $f(R)$. Note that for the Willamette River case,

$$f(R) = W_{i,0} - RW_{i,0} \qquad \text{.......... (24)}$$

where $W_{i,0}$ is discharger i's BOD discharge rate when there is minimal treatment. $W_{i,0}$ is assumed to correspond to Treatment Option Level 1, as defined by Van Note et al [1975], for the WWTPs, and Treatment Option Level 0, as defined by E.C. Jordan [1979], for the PPMs. As for the Athabasca River case,

$$f(R) = RP_i \qquad \text{.......... (25)}$$

where P_i is discharger i's maximum possible daily production rate, as originally given by Macdonald and Hamilton [1989] and reproduced in Tables B-18 to B-22 in Appendix B. Note that R, which is a constant, is not an input variable but is instead, a function of W_i and P_i.

4.2.2 TDP Equilibrium Sub-Model

Once the initial permit allocation is determined, the final TDP equilibrium can be found. To find the final TDP equilibrium, this study assumes ideal market conditions such that all trading will eventually lead to some least-cost solution i.e. the individual dischargers would trade solely to minimize costs and maximize profits. Market imperfections, like the presence of transaction costs, hoarding, or other inhibitions to trading, are ignored. Possible regulatory uncertainties, personal preferences and such other factors are also ignored.

Under such assumptions, the final TDP equilibrium can be found by optimizing to

$$MIN\ \ Cost = \sum_{i=1}^{I} A_i - \sum_{i=1}^{I}\sum_{k=1}^{K} G_{ik} w_{ik} \quad \text{.........} \ (20)$$

Subject to the constraints

$$L_{ik} \le w_{ik} \le U_{ik}, \ \ \text{all } i, \text{all } k \quad \text{..........} \ (21)$$

$$\sum_{i} W_i \le W_{tot}, \text{all } i \quad \text{.........} \ (26)$$

where W_{tot} is the total amount of permits issued. W_{tot} is a constant and an input variable derived from the initial permit allocation sub-model. As before, w_{ik} are the decision variables. Equation (20) is the objective function. Equations (21) and (26) are the model constraints. Equation (26) limits the total discharge so that it does not exceed W_{tot}. Note that there is no water quality constraint. This is because the dischargers trade with regards only to their individual economics, and with total disregard to the environment. Thus, trading may render environmental quality worse or better, depending on the relative magnitudes of the dischargers' marginal waste abatement costs and a_{ij} values.

The w_{ik} obtained from the solution to the optimization problem given by the equations above, substituted into the environmental-response model (equation (8)) then give the water quality reliability after trading. By comparing this reliability with that from the initial permit allocation sub-model, a quantitative measure of the potential impact that trading might have on the reliability of the water quality meeting environmental standards can then be made.

5.0 RESULTS AND DISCUSSION

The methodology described in Section 4.0 was applied, for both rivers, for a range of before-trading reliabilities (denoted as α in equation (22)). Refer to Figures 16 to 21, as well as Tables 8 and 9 and Tables C-1 to C-6 in Appendix C.

Figures 16 and 17 give the cost-reliability tradeoff for the Willamette River and the Athabasca River cases respectively. For each case, the before-trading tradeoff is compared to the after-trading tradeoff, and both are further compared to the least-cost tradeoff, where the least-cost tradeoff is based on the most economical solution possible to achieve a given level of reliability. The least-cost solution can be found in the same manner as the TDP solution, but without having to consider the limit on the total number of permits issued (equation (26)), and having to include in a check on the water quality reliability (equation (22)). The least-cost solution, though practically inapplicable due to its inequity, is provided as a benchmark to evaluate the economic efficiency of the other two solutions.

As expected, the tradeoff curves, whether before-trading, after-trading or least-cost, all show that cost and reliability are inversely proportional to each other i.e. the higher the desired level of reliability, the higher the cost of attaining it. Note the arrows in Figures 16 and 17. The arrows are an indication of how trading might affect the system. For the Willamette River, the arrows are pointing downward and to the right. For the Athabasca River, the arrows are for the most part pointing downwards and to the left. This means that, in terms of cost, trading is advantageous for both cases. However, in terms of reliability, trading is advantageous only for the Willamette River case. For the Athabasca River, trading makes worse the reliability.

For further details, refer to Tables C-1 to C-6 in Appendix C, which gives the wasteload allocations and cost figures for the before-trading, after-trading and least-cost scenarios.

Figures 18 and 20 show more clearly the effect of trading on the reliability. For the Willamette River, trading seems to have little effect on the reliability i.e. the reliability remains almost constant with trading. The effect of trading is more obvious for the Athabasca River. This is possibly due to the Athabasca River being a larger system but with fewer controlled dischargers that are located relatively farther from each other. The Willamette River is four times less the length of the portion of the Athabasca River modeled here, but has three times the number of controlled dischargers that are located relatively closer to each other. This difference between the Willamette and Athabasca systems is reflected in their a_{ij} distributions. The a_{ij} mean, variance and covariances for one discharger are more different from those for another for the Athabasca River than for the Willamette River. This means that the Athabasca River is more sensitive to locational effects due to trading than is the Willamette River.

This observation raises an interesting question of when locational effects are significant and when not. For a deterministic system, the answer is simple. Locational effects are negligible when the deterministic a_{ij} for one discharger is close enough to the a_{ij} for another. However, for stochastic systems where the effects of changes in the mean could either be reinforced or diminished by changes in the standard deviation, the answer is not as straightforward. Section 3.2 attempts to give some insight to this question. However, suggestions given there are by no means final.

Tables 8 and 9 give the F, $f_{1,j}$ and $f_{2,j}$ ratios, as well as others details of system changes due to trading for the two rivers analyzed. It is interesting to note that for both systems, the mean dominates the standard deviation. For the Willamette River, the standard deviation is unchanging with trading. For the Athabasca River, the standard deviation changes with trading but those changes are always smaller than the corresponding changes in the mean. This is reflected by the Willamette River's $f_{2,j}$ ratios that are always unity and the Athabasca River's $f_{2,j}$ ratios that are always, though not unity, nearer to unity than their corresponding $f_{1,j}$ ratios. In other words, the reliability tends to follow the mean- that is, where there is an increase in the mean, there will be an increase in the reliability and vice versa- while the standard deviation is almost a non-issue.

For further illustration, refer to Figures 19 and 21, which show, for the before-trading reliability of 85%, how the DO concentration probability distribution function (PDF) and the cumulative PDF change with trading, for the Willamette and Athabasca Rivers respectively. For the Willamette River, trading shifts the mean of the PDF to the right while maintaining its spread. For the Athabasca River, trading shifts the mean to the left while very slightly increasing its spread.

It is uncertain if this observation, of the mean dominating the standard deviation, is typical for most, if not all, environmental systems. If it is, the impact of trading on the water quality reliability can be deduced by simply looking at the impact of trading on the water quality mean. And thus, the need for complicated stochastic models is eliminated, and instead simpler deterministic models should suffice. However, if the mean is not always the dominating factor, is it then helpful to understand the conditions under which the mean dominates, or otherwise. The answers to these questions raised are not immediately obvious, and it remains a challenge to find them.

The policy-maker might find the findings so far useful. It is true that, considering the many unresolved uncertainties involved in modeling a river accurately and predicting how the various TDP participants might react, it is hard to say if it is any more accurate to design a TDP program based on reliability than to design it based on some deterministic conservative scenario. Nevertheless, it is believed that this work is a step forward in giving a more complete picture of the effect trading might have on the environment.

Like all other studies, this study is not without assumptions. Firstly, there is the assumption of ideal market conditions with zero transaction costs. In reality, especially when the number of program participants is limited as it is for the Willamette and Athabasca Rivers, and if there is a lack of an effective central authority to connect potential buyers to potential sellers, ideal market conditions are hard to achieve. This means that in reality, it is difficult to predict how trading might proceed, and hence difficult to predict how trading might affect the environment.

Secondly, the theory and methodology presented in this study are best applicable for cases where there is a single critical point such that as long as the desired level of reliability at that one point is satisfied, the reliability of the entire system on the overall will also be satisfied. It is also suitable to be applied to multi-critical point systems where the critical points are co-dependent such that the environmental quality at the different points tend to vary together so that the on the overall, the system reliability equals the reliability at the constraining point. However, for multi-critical point cases where the critical points are not co-dependent, the MFOSM method is not the most appropriate as it is then unable to calculate for the overall system reliability, but only the individual reliability at each critical point. Thus, for such cases, other methods such as those based on multiple realizations [Morgan et al, 1993; Takyi and Lence, 1999] are more fitting.

Finally, there is the issue of whether or not reliability by itself is an adequate measure of environmental quality. Reliability is simply a measure of the probability of the water quality standard being violated. It bears no indication of the vulnerability [Hashimoto et al, 1982] of the system, which is a measure of the severity of the violation. Neither does it account for the resilience [Fiering, 1982; Holling, 1996] of the system, which is a measure of the time required for the system to recover from a violation. A more comprehensive measure of environmental quality would include these other indices.

Nonetheless, the methods and concepts described in this study are computationally convenient and easy to implement, and should suffice for many analyses of reliability as it relates to trading.

Table 8: System changes due to trading for the Athabasca River for the DO concentration standard of 5 mg/L.

Desired Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.20	0.10
First Possible Critical Point at RK 449																	
Before-trade mean (mg/L)	6.36	5.99	5.78	5.64	5.53	5.42	5.33	5.25	5.16	5.08	5.00	4.92	4.83	4.74	4.64	4.41	4.09
Before-trade std deviation (mg/L)	0.59	0.60	0.61	0.62	0.62	0.63	0.64	0.64	0.65	0.65	0.66	0.66	0.67	0.67	0.68	0.70	0.73
Before-trade reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.20	0.10
After-trade mean (mg/L)	5.90	5.90	5.72	5.52	5.47	5.46	5.41	5.24	5.07	4.91	4.87	4.84	4.80	4.66	4.42	3.86	3.06
After-trade std deviation (mg/L)	0.62	0.62	0.63	0.64	0.64	0.64	0.64	0.65	0.66	0.67	0.67	0.67	0.67	0.68	0.71	0.76	0.84
After-trade reliability	0.93	0.93	0.87	0.79	0.77	0.76	0.74	0.64	0.54	0.45	0.42	0.40	0.38	0.31	0.21	0.07	0.01
Second Possible Critical Point at RK 811																	
Before-trade mean (mg/L)	6.74	6.39	6.21	6.08	5.97	5.88	5.80	5.72	5.65	5.57	5.50	5.42	5.34	5.26	5.17	4.96	4.67
Before-trade std deviation (mg/L)	0.46	0.53	0.57	0.60	0.62	0.64	0.66	0.67	0.69	0.70	0.72	0.74	0.75	0.77	0.79	0.83	0.89
Before-trade reliability	1.00	1.00	0.98	0.96	0.94	0.92	0.89	0.86	0.83	0.79	0.75	0.72	0.68	0.63	0.59	0.48	0.35
After-trade mean (mg/L)	6.35	5.96	5.76	5.66	5.64	5.60	5.55	5.47	5.39	5.32	5.29	5.27	5.25	5.18	5.05	4.74	4.32
After-trade std deviation (mg/L)	0.56	0.64	0.68	0.70	0.71	0.71	0.71	0.73	0.75	0.76	0.77	0.77	0.77	0.79	0.82	0.89	1.00
After-trade reliability	0.99	0.93	0.87	0.83	0.82	0.80	0.78	0.74	0.70	0.66	0.65	0.64	0.63	0.59	0.52	0.39	0.25
Statistics for Critical of Points RK 449 and RK 811																	
Before-trade reliability index, $\beta_{j,old}$	2.33	1.64	1.28	1.04	0.84	0.67	0.52	0.39	0.25	0.13	0.00	-0.13	-0.25	-0.39	-0.52	-0.84	-1.26
After-trade reliability index, $\beta_{j,new}$	1.45	1.45	1.14	0.81	0.73	0.72	0.63	0.36	0.11	-0.13	-0.19	-0.24	-0.30	-0.50	-0.82	-1.51	-2.30
Mean f ratio, $f_{1,j}$	0.66	0.91	0.92	0.81	0.89	1.08	1.22	0.96	0.44	-1.08	-	1.97	1.19	1.31	1.62	1.94	2.12
Standard deviation f ratio, $f_{2,j}$	1.06	1.03	1.03	1.03	1.02	1.01	1.01	1.02	1.02	1.03	-	1.02	1.01	1.01	1.03	1.08	1.16
Overall F ratio, F_j	0.62	0.88	0.89	0.78	0.87	1.06	1.21	0.94	0.43	-1.05	-	1.94	1.18	1.29	1.56	1.79	1.83
Change in reliability	-0.06	-0.02	-0.03	-0.06	-0.03	0.01	0.04	-0.01	-0.06	-0.10	-0.08	-0.05	-0.02	-0.04	-0.09	-0.13	-0.09

Table 9: System changes due to trading for the Willamette River for the DO concentration standard of 5 mg/L.

Desired Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
Critical Point at RK 300																	
Before-trade mean (mg/L)	6.34	5.98	5.78	5.64	5.52	5.42	5.33	5.25	5.16	5.08	5.00	4.92	4.83	4.73	4.63	4.52	4.39
Before-trade std deviation (mg/L)	0.58	0.59	0.60	0.61	0.62	0.63	0.64	0.64	0.65	0.66	0.66	0.67	0.68	0.69	0.70	0.71	0.73
Before-trade reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
After-trade mean (mg/L)	6.37	6.03	5.86	5.71	5.59	5.50	5.41	5.32	5.23	5.14	5.05	4.95	4.86	4.76	4.66	4.54	4.39
After-trade std deviation (mg/L)	0.58	0.59	0.61	0.61	0.62	0.63	0.63	0.64	0.65	0.66	0.66	0.67	0.68	0.69	0.70	0.71	0.73
After-trade reliability	0.99	0.96	0.92	0.88	0.83	0.79	0.74	0.69	0.64	0.58	0.53	0.47	0.42	0.36	0.31	0.26	0.20
Statistics for Critical Point RK 300																	
Before-trade reliability index, $\beta_{j,old}$	2.33	1.64	1.28	1.04	0.84	0.67	0.52	0.39	0.25	0.13	0.00	-0.13	-0.25	-0.39	-0.52	-0.67	-0.84
After-trade reliability index, $\beta_{j,new}$	2.37	1.74	1.42	1.16	0.96	0.80	0.65	0.50	0.35	0.21	0.07	-0.07	-0.21	-0.36	-0.49	-0.65	-0.84
Mean f ratio, $f_{1,j}$	1.02	1.06	1.11	1.12	1.14	1.19	1.24	1.29	1.38	1.66	-	0.57	0.83	0.92	0.94	0.97	0.99
Standard deviation f ratio, $f_{2,j}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00
Overall F ratio, F_j	1.02	1.06	1.11	1.12	1.14	1.19	1.25	1.30	1.39	1.66	-	0.57	0.83	0.92	0.94	0.97	0.99
Change in reliability	0.00	0.01	0.02	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.00

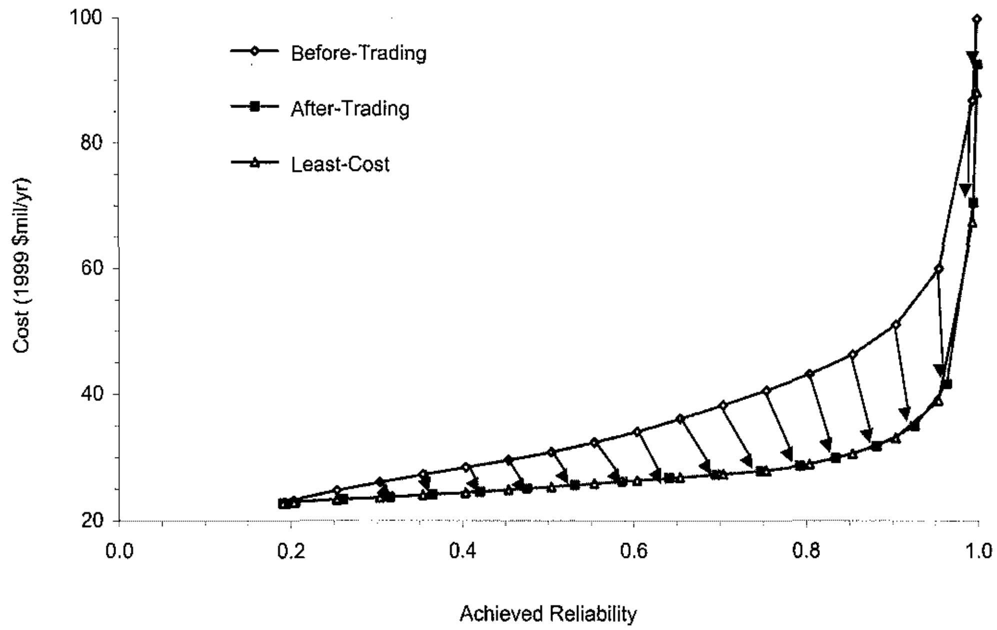

Figure 16: The effect of trading on the cost-reliability tradeoff for the Willamette River.

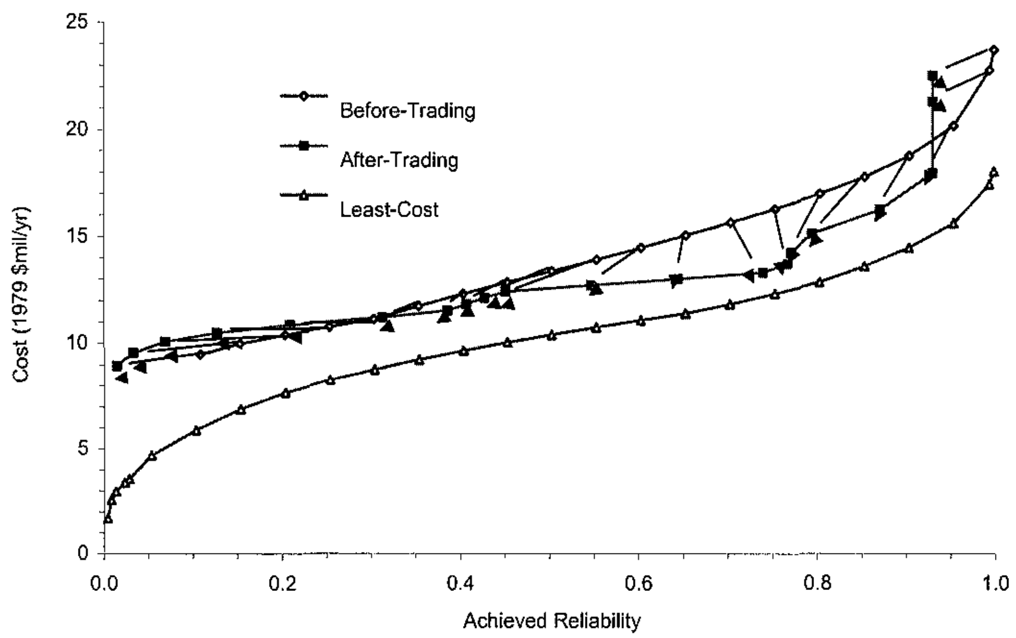

Figure 17: The effect of trading on the cost-reliability tradeoff for the Athabasca River.

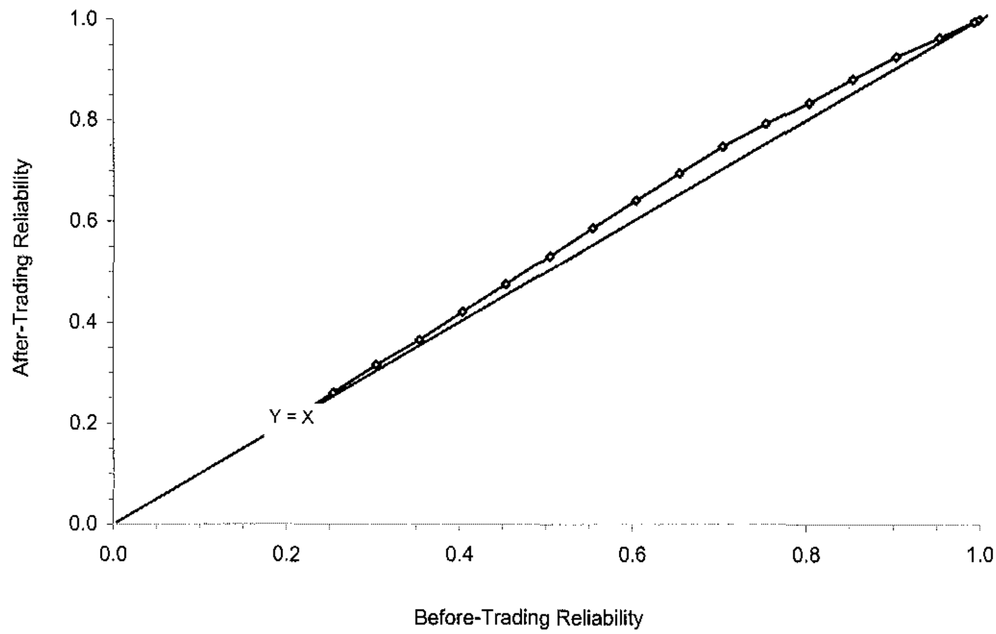

Figure 18: The effect of trading on the DO concentration reliability for the Willamette River.

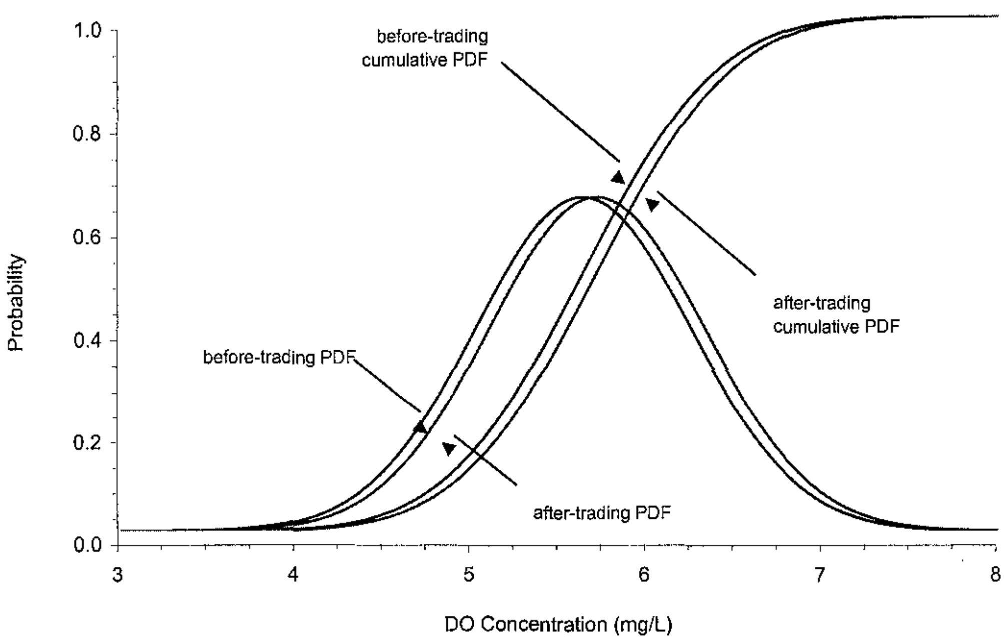

Figure 19: The effect of trading on the DO concentration probability distribution function (PDF) and cumulative PDF for the Willamette River, for the before-trading reliability of 0.85.

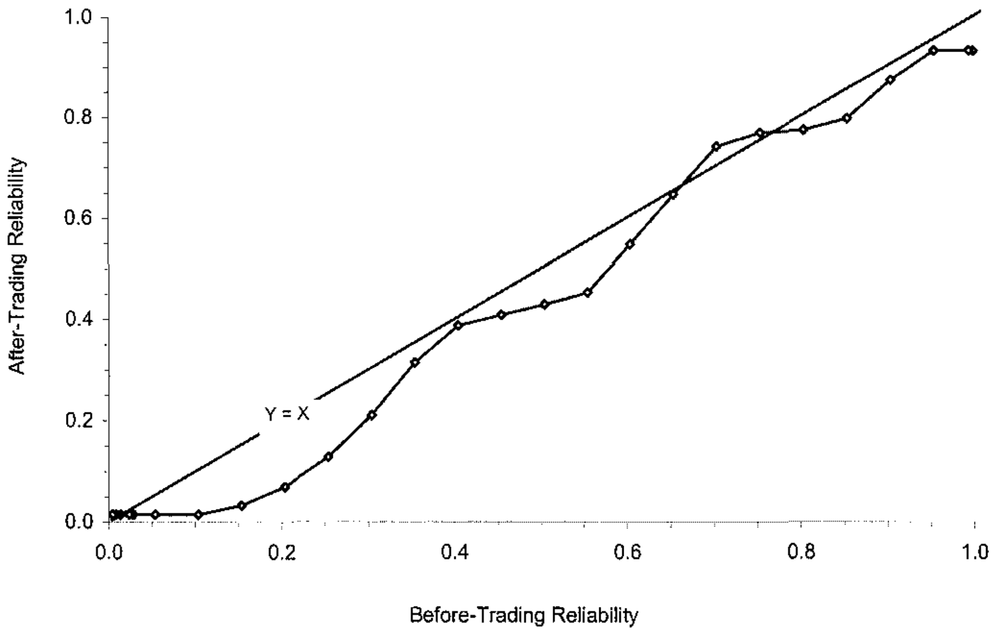

Figure 20: The effect of trading on the DO concentration reliability for the Athabasca River.

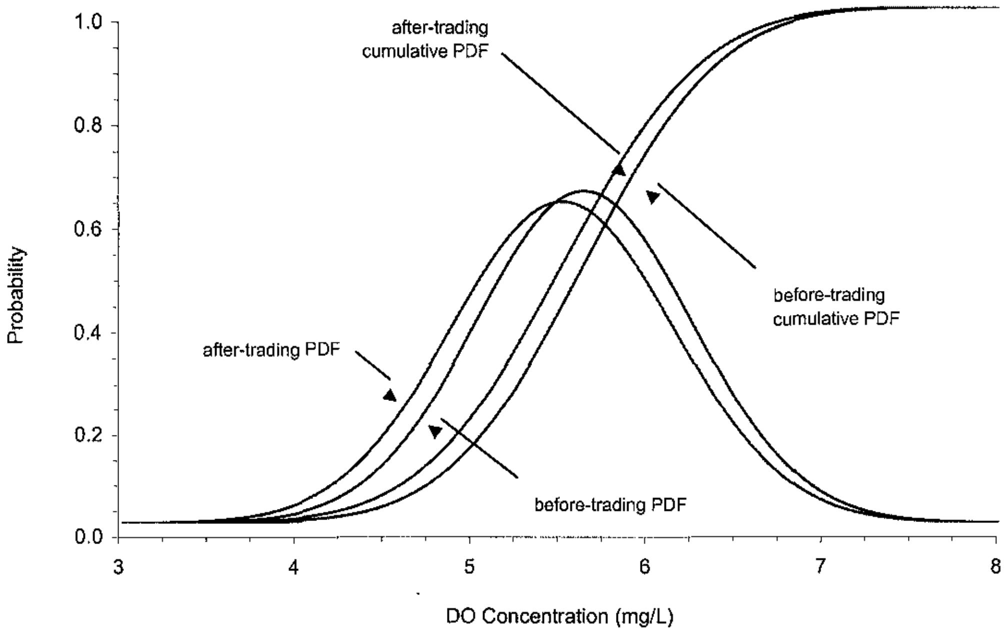

Figure 21: The effect of trading on the DO concentration probability distribution function (PDF) and cumulative PDF for the Athbasca River, for the before-trading reliability of 0.85.

6.0 SUMMARY AND CONCLUSIONS

A review of some of the uncertainties facing the successful implementation of a tradable discharge permit program is made. Uncertainties due to market unpredictability, together with modeling difficulties, make it a challenge to be able to predict accurately *a priori* how a trading program might proceed. This study focuses on the modeling uncertainties associated with environmental variables, such as stream flow and temperature, that are, due to their randomness, more difficult to characterize than their deterministic counterparts usually present in closed controlled systems. To estimate the effects of trading on the stochastic environment, the MFOSM method is applied to two riverine case studies i.e. the Willamette and the Athabasca Rivers. The before- and after-trading reliabilities of each river's DO concentration meeting the pre-set standard of 5 mg/L are calculated and compared.

It is confirmed that trading does indeed affect the reliability of a system, albeit only slightly in the examples presented here for any reasonable target reliability to be achieved. This is primarily due to the inherent characteristic of trading programs that redistributes the system's discharge locations. Whether the effect of trading is negative or positive depends on the system's individual characteristics. For the Willamette River, trading improves the reliability, but for the Athabasca River, trading degrades the reliability.

It is also found that trading affects a system's mean more than its standard deviation, at least for the Willamette and Athabasca Rivers. This means that the reliability, which is a function of the mean and standard deviation, tends to change with the mean as whatever corresponding changes in the standard deviation are relatively insignificant. However, no conclusion can be made of whether or not this observation is true for all environmental systems. If it is true that the mean dominates the standard deviation always, then the need for complex stochastic models is reduced as simpler deterministic models become sufficient. And if the opposite applies, then it is useful to understand the circumstances under which the mean and the standard deviation are equally dominant, or under which the standard deviation dominates.

There remains much work to be undertaken before the many uncertainties facing a trading program can be fully quantified, assuming that they are quantifiable. Permit trading bears much potential as a cost-effective pollution control tool. Nonetheless, its full potential can only be realized if its uncertainties are well understood.

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Table A-1: Input random variable distributions for the Willamette River stochastic environmental response model.

Random Variable	Parameter 1	Parameter 2	Parameter 3	Lower Bound	Distribution Type
Flow - Willamette River at RK 0 (m^3/s)	mean = 62.3	std dev = 13.7	-	2.8	Lognormal
Flow - McKenzie River (m^3/s)	mean = 68.3	std dev = 12.5	-	2.8	Lognormal
Flow - Santiam River (m^3/s)	location = 0	shape = 6.1	scale = 41.8	2.8	Weibull
Flow - Clackamas River (m^3/s)	mean = 26.2	std dev = 4.8	-	2.8	Lognormal
Temperature - Salem (°C)	mean = 21.2	std dev = 1.2	-	1.7	Lognormal
SOD - RK 0 to RK 42 (g/m^2-d)	mean = 2.12	std dev = 0.6	-	0.0	Normal
SOD - RK 42 RK 81 (g/m^2-d)	mean = 1.98	std dev = 0.52	-	0.0	Normal
Reaeration Coefficient (K_a) Error Term (-)	mean = -0.111	std dev = 0.155	-	-4.0	Normal

Notes:

1. The K_a error term is defined as error = $\log_{10}(K_a$ by the O'Connor & Dobbins Eqn) - $\log_{10}$ (real K_a). K_a is in units of 1/d.

2. Table from Tolson [2000].

Table A-2: Correlation coeffcient matrix for the Willamette River stochastic environmental response model.

Variable No.	1	2	3	4	5	6	7	8
1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	1.0	0.7	-0.8	0.0	0.0	0.0
4	0.0	0.0	0.7	1.0	-0.7	0.0	0.0	0.0
5	0.0	0.0	-0.8	-0.7	1.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

Notation

Variable 1 = Flow - Willamette River at RK 0 (m^3/s)

Variable 2 = Flow - McKenzie River (m^3/s)

Variable 3 = Flow - Santiam River (m^3/s)

Variable 4 = Flow - Clackamas River (m^3/s)

Variable 5 = Temperature - Salem (°C)

Variable 6 = SOD - RK 0 to RK 42 (g/m^2-d)

Variable 7 = SOD - RK 42 RK 81 (g/m^2-d)

Variable 8 = Reaeration Coefficient (K_a) Error Term (-)

Notes:

1. Table from Tolson [2000].

Table A-3: Historical low-flow data for the Athabasca River.

Year	Minimum Daily Flow, m^3/s			
	at Hinton	at Whitecourt	at Athabasca	at McMurray
1962	11.0	32.8	62.6	118.0
1963	10.8	29.7	81.0	183.0
1964	15.0	23.4	64.6	117.0
1965	15.7	30.3	98.8	164.0
1966	17.2	38.5	77.9	179.0
1967	24.4	28.2	59.5	118.0
1968	27.5	56.1	61.0	108.0
1969	31.1	43.9	55.2	108.0
1970	19.8	42.5	62.3	104.0
1971	21.5	38.8	69.4	138.0
1972	27.8	44.2	86.1	147.0
1973	29.7	55.8	110.0	159.0
1974	26.9	42.5	92.6	173.0
1975	28.3	39.6	96.0	187.0
1976	21.0	42.2	87.8	130.0
1977	19.3	45.3	85.0	144.0
1978	25.8	43.0	94.0	182.0
1979	17.5	43.4	81.0	147.0
1980	18.6	38.0	85.1	152.0
1981	17.0	48.6	55.6	92.0
1982	22.5	36.0	58.0	95.0
1983	25.0	38.9	84.0	146.0
1984	20.0	42.0	70.7	167.0
1985	18.2	40.7	90.0	164.0
1986	17.1	47.7	100.0	166.0
1987	25.0	52.0	59.5	104.0
1988	23.2	47.2	55.0	88.6
1989	19.4	31.3	54.8	128.0
1990	25.0	50.1	81.8	155.0
1991	24.5	40.0	81.7	136.0

Notes:

1. Table compiled by Eheart [Personal communication, 2002].

Table A-4: 30 realizations of a_{ij} and B_j for the Athabasca River's Reach 27 at RK 449.

Year	a_{ij} (mg/L per ton BOD_5/d)					Background DO, B_j (mg/L)
	for Welwood, i=1	for ANC, i=2	for Millar, i=3	for AEC, i=4	for Al-Pac, i=5	
1962	-0.6200	-0.1153	-0.5518	0.0000	0.0000	8.4159
1963	-0.5483	-0.1029	-0.4972	0.0000	0.0000	7.6741
1964	-0.7477	-0.1134	-0.5889	0.0000	0.0000	7.6688
1965	-0.5266	-0.0935	-0.4444	0.0000	0.0000	7.3399
1966	-0.5736	-0.1043	-0.4766	0.0000	0.0000	8.3151
1967	-0.8184	-0.1182	-0.5882	0.0000	0.0000	8.2531
1968	-0.5847	-0.1091	-0.4660	0.0000	0.0000	9.6938
1969	-0.7175	-0.1180	-0.5306	0.0000	0.0000	9.3878
1970	-0.6357	-0.1133	-0.5113	0.0000	0.0000	9.0193
1971	-0.6384	-0.1095	-0.5019	0.0000	0.0000	8.5921
1972	-0.5597	-0.0989	-0.4377	0.0000	0.0000	8.4290
1973	-0.4437	-0.0864	-0.3648	0.0000	0.0000	8.4167
1974	-0.5427	-0.0960	-0.4270	0.0000	0.0000	8.1867
1975	-0.5509	-0.0948	-0.4267	0.0000	0.0000	7.9654
1976	-0.5368	-0.0984	-0.4391	0.0000	0.0000	8.2690
1977	-0.5215	-0.0992	-0.4373	0.0000	0.0000	8.4880
1978	-0.5314	-0.0953	-0.4226	0.0000	0.0000	8.1771
1979	-0.5350	-0.1017	-0.4527	0.0000	0.0000	8.4928
1980	-0.5568	-0.1003	-0.4581	0.0000	0.0000	8.1044
1981	-0.6038	-0.1158	-0.5096	0.0000	0.0000	9.5471
1982	-0.7334	-0.1183	-0.5557	0.0000	0.0000	8.8209
1983	-0.5887	-0.1008	-0.4583	0.0000	0.0000	8.1992
1984	-0.6007	-0.1079	-0.4862	0.0000	0.0000	8.7206
1985	-0.5216	-0.0975	-0.4379	0.0000	0.0000	8.1319
1986	-0.4536	-0.0919	-0.3989	0.0000	0.0000	8.2491
1987	-0.6079	-0.1117	-0.4844	0.0000	0.0000	9.5747
1988	-0.6561	-0.1168	-0.5173	0.0000	0.0000	9.5259
1989	-0.7824	-0.1220	-0.5941	0.0000	0.0000	8.6312
1990	-0.5331	-0.0997	-0.4317	0.0000	0.0000	8.8076
1991	-0.5893	-0.1019	-0.4612	0.0000	0.0000	8.3165

Notes:

1. Table from Eheart [Personal communication, 2002].

Table A-5: 30 realizations of a_{ij} and B_j for the Athabasca River's Reach 37 at RK 811.

Year	a_{ij} (mg/L per ton BOD_5/d)					Background DO, B_j (mg/L)
	for Welwood, i=1	for ANC, i=2	for Millar, i=3	for AEC, i=4	for Al-Pac, i=5	
1962	-0.3053	-0.0564	-0.2424	-0.1094	-0.2845	8.6278
1963	-0.1994	-0.0374	-0.1626	-0.0915	-0.1909	8.7025
1964	-0.3305	-0.0470	-0.2270	-0.1291	-0.2853	8.6569
1965	-0.2374	-0.0424	-0.1786	-0.1075	-0.2037	8.7582
1966	-0.2376	-0.0438	-0.1753	-0.0838	-0.1954	8.6969
1967	-0.3806	-0.0515	-0.2348	-0.1134	-0.2863	8.6466
1968	-0.4260	-0.0839	-0.2995	-0.0519	-0.3069	8.6386
1969	-0.4417	-0.0724	-0.2826	-0.0696	-0.3109	8.6243
1970	-0.4055	-0.0732	-0.2866	-0.0963	-0.3155	8.6337
1971	-0.3194	-0.0547	-0.2200	-0.0950	-0.2466	8.6711
1972	-0.3087	-0.0562	-0.2127	-0.1005	-0.2273	8.7349
1973	-0.2797	-0.0593	-0.2063	-0.0989	-0.2052	8.8048
1974	-0.2639	-0.0480	-0.1835	-0.0928	-0.1968	8.7489
1975	-0.2476	-0.0434	-0.1690	-0.0901	-0.1836	8.7587
1976	-0.3201	-0.0606	-0.2323	-0.1153	-0.2501	8.7353
1977	-0.2913	-0.0579	-0.2178	-0.1001	-0.2316	8.7185
1978	-0.2501	-0.0463	-0.1762	-0.0892	-0.1883	8.7501
1979	-0.2817	-0.0555	-0.2126	-0.0968	-0.2293	8.7028
1980	-0.2744	-0.0503	-0.2002	-0.1031	-0.2216	8.7195
1981	-0.4431	-0.0882	-0.3315	-0.0657	-0.3539	8.5869
1982	-0.4535	-0.0713	-0.2978	-0.1122	-0.3429	8.6247
1983	-0.3044	-0.0526	-0.2081	-0.1051	-0.2294	8.7260
1984	-0.2665	-0.0486	-0.1904	-0.0773	-0.2095	8.6762
1985	-0.2541	-0.0491	-0.1903	-0.0972	-0.2065	8.7315
1986	-0.2441	-0.0529	-0.1939	-0.0962	-0.2013	8.7571
1987	-0.4327	-0.0828	-0.3034	-0.0600	-0.3176	8.6265
1988	-0.4920	-0.0894	-0.3396	-0.0703	-0.3653	8.5992
1989	-0.3419	-0.0508	-0.2247	-0.0911	-0.2699	8.6165
1990	-0.2927	-0.0575	-0.2103	-0.0847	-0.2192	8.7147
1991	-0.3234	-0.0567	-0.2224	-0.1085	-0.2440	8.7189

Notes:

1. Table from Eheart [Personal communication, 2002].

Tables B-1 to B-11: Willamette River WWTP Cost Data

Note 1: Cost figures are in 1999 values and taken from Van Note et al [1975] and Tolson [2000].

Note 2: Effluent flowrates, and data for the raw wasteloads, are taken from Tolson [2000].

Note 3: Cost figures for the 100% removal treatment option (all) are extrapolated from the cost figures for the other treatment options.

Note 4: The BOD_5 to BOD_u conversion factor is 2.5 for all the WWTPs [Tolson, 2000; Tetra Tech, 1993].

i = Metropolitan W/W Management Commission

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	39.61	0.0	307.50	0
1	39.61	80.6	59.66	3.612
2	39.61	90.6	28.91	3.912
3	39.61	94.2	17.84	4.642
4	39.61	97.1	8.92	5.812
5	39.61	97.7	7.07	7.056
6	39.61	99.1	2.77	9.405
All	39.61	100.0	0.00	11.022

i = City of Salem

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	47.65	0.0	740.00	0
1	47.65	80.6	143.56	4.171
2	47.65	90.6	69.56	4.531
3	47.65	94.2	42.92	5.374
4	47.65	97.1	21.46	6.689
5	47.65	97.7	17.02	8.162
6	47.65	99.1	6.66	10.938
All	47.65	100.0	0.00	12.850

i = City of Albany

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	7.89	0.0	565.00	0
1	7.89	80.6	109.61	1.273
2	7.89	90.6	53.11	1.342
3	7.89	94.2	32.77	1.610
4	7.89	95.4	25.99	1.819
5	7.89	97.1	16.39	2.020
6	7.89	98.1	10.74	2.638
7	7.89	99.1	5.09	2.865
All	7.89	100.0	0.00	3.245

i = City of Corvalis

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	9.59	0.0	527.50	0
1	9.59	80.6	102.34	1.421
2	9.59	90.6	49.59	1.505
3	9.59	94.2	30.60	1.803
4	9.59	95.4	24.27	2.046
5	9.59	97.1	15.30	2.270
6	9.59	98.1	10.02	2.995
7	9.59	99.1	4.75	3.244
All	9.59	100.0	0.00	3.682

i = City of Newberg

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	2.48	0.0	522.50	0
1	2.48	80.6	101.37	0.701
2	2.48	90.6	49.12	0.728
3	2.48	92.8	37.62	0.896
4	2.48	94.2	30.31	0.904
5	2.48	95.4	24.04	1.015
6	2.48	96.4	18.81	1.093
7	2.48	97.1	15.15	1.100
8	2.48	98.1	9.93	1.421
9	2.48	99.1	4.70	1.556
All	2.48	100.0	0.00	1.761

i = City of Wilsonville

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	2.63	0.0	700.00	0
1	2.63	80.6	135.80	0.575
2	2.63	90.6	65.80	0.593
3	2.63	92.8	50.40	0.731
4	2.63	94.2	40.60	0.751
5	2.63	95.4	32.20	0.787
6	2.63	96.4	25.20	0.875
7	2.63	97.1	20.30	0.894
8	2.63	98.1	13.30	1.150
9	2.63	99.1	6.30	1.223
All	2.63	100.0	0.00	1.371

i = City of Portland

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	97.47	0.0	750.00	0
1	97.47	80.6	145.50	7.266
2	97.47	90.6	70.50	7.956
3	97.47	94.2	43.50	9.474
4	97.47	97.1	21.75	11.589
5	97.47	97.7	17.25	13.820
6	97.47	99.1	6.75	19.201
All	97.47	100.0	0.00	22.660

i = Tri-City Service District

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	9.28	0.0	687.50	0
1	9.28	80.6	133.38	1.395
2	9.28	90.6	64.63	1.476
3	9.28	94.2	39.88	1.767
4	9.28	95.4	31.63	2.006
5	9.28	97.1	19.94	2.223
6	9.28	98.1	13.06	2.924
7	9.28	99.1	6.19	3.173
All	9.28	100.0	0.00	3.601

i = Clackamas Co. Service District #1

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	11.14	0.0	825.00	0
1	11.14	80.6	160.05	1.548
2	11.14	90.6	77.55	1.643
3	11.14	94.2	47.85	1.963
4	11.14	95.4	37.95	2.234
5	11.14	97.1	23.93	2.476
6	11.14	97.7	18.98	2.746
7	11.14	99.1	7.43	3.558
All	11.14	100.0	0.00	4.080

i = Oak Lodge Sanitary District

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	4.02	0.0	550.00	0
1	4.02	80.6	106.70	0.883
2	4.02	90.6	51.70	0.921
3	4.02	94.2	31.90	1.125
4	4.02	95.4	25.30	1.235
5	4.02	97.1	15.95	1.390
6	4.02	98.1	10.45	1.803
7	4.02	99.1	4.95	1.927
All	4.02	100.0	0.00	2.169

i = City of Canby

Trt Opt	V Flow (ft3/s)	% Remv	BODu Conc (mg/L)	Cost (mil$/yr)
Raw	1.55	0.0	475.00	0
1	1.55	80.6	92.15	0.575
2	1.55	90.6	44.65	0.593
3	1.55	92.8	34.20	0.731
4	1.55	94.2	27.55	0.751
5	1.55	95.4	21.85	0.787
6	1.55	96.4	17.10	0.875
7	1.55	97.1	13.78	0.894
8	1.55	98.1	9.03	1.150
9	1.55	99.1	4.28	1.223
All	1.55	100.0	0.00	1.371

Tables B-12 to B-17: Willamette River PPM Cost Data

Note 1: Cost figures are in 1999 values and taken from E.C. Jordan [1979] and Tolson [2000].

Note 2: The PPM production rates are taken from Tolson [2000].

Note 3: Cost figures for the 100% removal treatment option (all) are extrapolated from the cost figures for the other treatment options.

Note 4: The BOD_5 to BOD_u conversion factor is 4.1 for all the PPMs, except for Pope and Talbot (conversion factor = 5.5) and James River (conversion factor = 2.7) [Tolson, 2000; Tetra Tech, 1993].

i = Pope and Talbot Inc.

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	164.70	45.10	165.0	0.000
1	137.60	37.68	165.0	1.458
2	123.00	33.68	165.0	1.921
3	123.00	33.68	82.5	8.589
4	123.00	33.68	27.5	20.539
All	123.00	33.68	0.0	26.514

* Production Rate = 670 ADT/d

i = James River Paper Co. Inc.

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	107.20	13.15	81.0	0.000
1	77.20	9.47	81.0	0.335
2	73.40	9.00	81.0	0.374
3	73.40	9.00	40.5	2.540
4	73.40	9.00	13.5	5.601
All	73.40	9.00	0.0	7.132

* Production Rate = 300 ADT/d

i = Willamette Industries Inc.

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	58.60	26.35	123.0	0.000
1	45.45	20.43	123.0	1.340
2	44.45	19.99	123.0	1.911
3	44.45	19.99	61.5	5.082
4	44.45	19.99	20.5	10.915
All	44.45	19.99	0.0	13.832

* Production Rate = 1100 ADT/d

i = Smufit Newsprint Corp. (Newberg)

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	110.90	40.80	123.0	0.000
1	88.00	32.37	123.0	1.134
2	71.90	26.45	123.0	1.284
3	71.90	26.45	61.5	4.376
4	71.90	26.45	20.5	9.562
All	71.90	26.45	0.0	12.155

* Production Rate = 900 ADT/d

i = Smufit Newsprint Corp. (Oregon)

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	67.60	19.34	951.2	0.000
1	57.50	16.45	951.2	0.439
2	55.50	15.88	492.0	1.894
3	55.50	15.88	123.0	3.757
All	55.50	15.88	0.0	4.230

* Production Rate = 700 ADT/d

i = Simpson Paper Co.

Trt Opt	V Flow (m^3/ADT)*	V Flow (ft^3/s)	BODu Conc (mg/L)	Cost (mil$/yr)
0	107.20	26.29	123.0	0.000
1	77.20	18.93	123.0	0.507
2	73.40	18.00	123.0	0.565
3	73.40	18.00	61.5	3.770
4	73.40	18.00	20.5	8.675
All	73.40	18.00	0.0	11.128

* Production Rate =600 ADT/d

Tables B-18 to B-22: Athabasca River PPM Cost Data

Note 1: Cost figures are in 1979 values and taken from E.C. Jordan [1979] and Eheart [Personal communication, 2002].

Note 2: The PPM production rates are taken from Macdonald and Hamilton [1989].

Note 3: Cost figures for the 100% removal treatment option (all) are extrapolated from the cost figures for the other treatment options.

i = Welwood of Canada Ltd.

Trt Opt	BOD5 Discharge (kg/ADT)*	BOD5 Discharge (kg/day)	Cost (mil$/yr)
0	9.88	10868	0.000
1	8.26	9086	0.707
2	7.38	8118	0.924
3	3.69	4059	4.300
4	1.23	1353	10.252
All	0.00	0	13.228

* Production Rate = 1100 ADT/d

i = Alberta Newsprint Company

Trt Opt	BOD5 Discharge (kg/ADT)*	BOD5 Discharge (kg/day)	Cost (mil$/yr)
0	4.20	2940	0.000
1	3.30	2310	0.319
2	3.20	2240	0.444
3	1.60	1120	1.345
4	0.50	350	2.779
All	0.00	0	3.430

* Production Rate = 700 ADT/d

i = Millar Western Pulp Ltd.

Trt Opt	BOD5 Discharge (kg/ADT)*	BOD5 Discharge (kg/day)	Cost (mil$/yr)
0	4.20	2856	0.000
1	3.30	2244	0.311
2	3.20	2176	0.433
3	1.60	1088	1.317
4	0.50	340	2.720
All	0.00	0	3.357

* Production Rate = 680 ADT/d

i = Alberta Energy Company (AEC)

Trt Opt	BOD5 Discharge (kg/ADT)*	BOD5 Discharge (kg/day)	Cost (mil$/yr)
0	4.20	1470	0.000
1	3.30	1155	0.189
2	3.20	1120	0.261
3	1.60	560	0.860
4	0.50	175	1.745
All	0.00	0	2.147

* Production Rate = 350 ADT/d

i = Alberta Pacific Forest Industries Inc.

Trt Opt	BOD5 Discharge (kg/ADT)*	BOD5 Discharge (kg/day)	Cost (mil$/yr)
0	9.88	14820	0.000
1	8.26	12390	0.926
2	7.38	11070	1.218
3	3.69	5535	5.553
4	1.23	1845	13.575
All	0.00	0	17.586

* Production Rate = 1500 ADT/d

Tables B-23 to B-33: Piecewise Linearization of the Willamette River WWTP Cost Data

i = Metropolitan W/W Management Commission

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	34.49	0.00
2	-0.06	12.42	0.00
3	-0.12	10.00	0.00
4	-0.52	10.00	3.10

i = City of Salem

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	99.87	0.00
2	-0.02	35.95	0.00
3	-0.05	28.96	0.00
4	-0.21	28.96	8.99

i = City of Albany

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	12.63	0.00
2	-0.06	4.55	0.00
3	-0.11	3.66	0.00
4	-0.33	3.66	1.14

i = City of Corvalis

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	14.33	0.00
2	-0.06	5.16	0.00
3	-0.11	4.16	0.00
4	-0.34	4.16	1.29

i = City of Newberg

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.02	3.66	0.00
2	-0.13	1.32	0.00
3	-0.18	1.06	0.00
4	-0.62	1.06	0.33

i = City of Wilsonville

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	5.21	0.00
2	-0.08	2.50	0.00
3	-0.12	0.89	0.00
4	-0.32	1.51	0.47

i = City of Portland

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	0.00	207.04	0.00
2	-0.02	74.53	0.00
3	-0.04	60.04	0.00
4	-0.18	12.42	0.00
5	-0.19	47.62	18.63

i = Tri-City Service District

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	18.07	0.00
2	-0.04	6.51	0.00
3	-0.09	5.24	0.00
4	-0.26	5.24	1.63

i = Clackamas Co. Service District #1

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	26.03	0.00
2	-0.03	9.37	0.00
3	-0.07	7.55	0.00
4	-0.17	1.56	0.00
5	-0.22	5.99	2.34

i = Oak Lodge Sanitary District

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.02	6.27	0.00
2	-0.09	2.26	0.00
3	-0.15	1.82	0.00
4	-0.43	1.82	0.56

i = City of Canby

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.03	2.08	0.00
2	-0.19	1.00	0.00
3	-0.30	0.35	0.00
4	-0.79	0.60	0.19

Tables B-34 to B-39: Piecewise Linearization of the Willamette River PPM Cost Data

i = Pope and Talbot Inc.

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.04	53.36	0.00
2	-0.08	78.69	0.00
3	-0.23	78.69	26.23

i = James River Paper Co. Inc.

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.04	9.51	0.00
2	-0.21	10.32	0.00
3	-0.44	10.32	3.44

i = Willamette Industries Inc.

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.07	20.59	0.00
2	-0.10	36.37	0.00
3	-0.25	34.80	11.60

i = Smufit Newsprint Corp. (Newberg)

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.03	49.97	0.00
2	-0.07	46.06	0.00
3	-0.17	46.06	15.35

i = Smufit Newsprint Corp. (Oregon)

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.01	77.84	0.00
2	-0.01	443.12	55.31

i = Simpson Paper Co.

Piece No., k	Gadient, Gik (mil$/yr per gBODu/s)	Up Bound, Uik (gBODu/s)	Low Bound, Lik (gBODu/s)
1	-0.02	28.87	0.00
2	-0.10	31.35	0.00
3	-0.23	31.35	10.45

Tables B-40 to B-44: Piecewise Linearization of the Athabasca River PPM Cost Data

i = Welwood of Canada Ltd.

Piece No., k	Gadient, Gik ($1000/yr per kgBOD5/d)	Up Bound, Uik (kgBOD5/d)	Low Bound, Lik (kgBOD5/d)
1	-2.20	4059	1353
2	-0.83	4059	0
3	-0.34	2750	0

i = Alberta Newsprint Company

Piece No., k	Gadient, Gik ($1000/yr per kgBOD5/d)	Up Bound, Uik (kgBOD5/d)	Low Bound, Lik (kgBOD5/d)
1	-1.86	1120	350
2	-0.86	1190	0
3	-0.51	630	0

i = Millar Western Pulp Ltd.

Piece No., k	Gadient, Gik ($1000/yr per kgBOD5/d)	Up Bound, Uik (kgBOD5/d)	Low Bound, Lik (kgBOD5/d)
1	-1.87	1088	340
2	-0.87	1156	0
3	-0.51	612	0

i = Alberta Energy Company (AEC)

Piece No., k	Gadient, Gik ($1000/yr per kgBOD5/d)	Up Bound, Uik (kgBOD5/d)	Low Bound, Lik (kgBOD5/d)
1	-2.30	560	175
2	-1.13	595	0
3	-0.60	315	0

i = Alberta Pacific Forest Industries Inc.

Piece No., k	Gadient, Gik ($1000/yr per kgBOD5/d)	Up Bound, Uik (kgBOD5/d)	Low Bound, Lik (kgBOD5/d)
1	-2.17	5535	1845
2	-0.78	5535	0
3	-0.32	3750	0

Table C-1: Before-trading wasteload allocation and cost figures for the Willamette River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
WWTP discharge allocation (gBODu/s)																	
1. Metropolitan	12.3	22.3	27.8	31.6	34.7	37.5	40.0	42.3	44.6	46.9	49.1	51.4	53.9	56.4	59.2	62.3	65.9
4. Corvalis	5.1	9.3	11.6	13.1	14.4	15.6	16.6	17.6	18.5	19.5	20.4	21.4	22.4	23.4	24.6	25.9	27.4
5. Albany	4.5	8.2	10.2	11.6	12.7	13.7	14.6	15.5	16.3	17.2	18.0	18.8	19.7	20.7	21.7	22.8	24.1
7. Salem	35.5	64.6	80.6	91.6	100.6	108.5	115.7	122.5	129.1	135.7	142.2	149.0	155.9	163.4	171.4	180.4	190.8
8. Newberg	1.3	2.4	3.0	3.4	3.7	4.0	4.2	4.5	4.7	5.0	5.2	5.5	5.7	6.0	6.3	6.6	7.0
10. Wilsonville	1.9	3.4	4.2	4.8	5.3	5.7	6.0	6.4	6.7	7.1	7.4	7.8	8.1	8.5	8.9	9.4	10.0
11. Canby	0.7	1.3	1.7	1.9	2.1	2.3	2.4	2.6	2.7	2.8	3.0	3.1	3.3	3.4	3.6	3.8	4.0
14. Tri-City	6.4	11.7	14.6	16.6	18.2	19.6	20.9	22.2	23.4	24.6	25.7	27.0	28.2	29.6	31.0	32.6	34.5
15. Portland	73.6	133.9	167.0	189.9	208.6	224.9	239.8	254.0	267.7	281.2	294.9	308.8	323.3	338.7	355.4	374.0	395.5
16. Oak Lodge	2.2	4.1	5.1	5.7	6.3	6.8	7.3	7.7	8.1	8.5	8.9	9.3	9.8	10.2	10.8	11.3	12.0
17. Clackamas	9.2	16.8	21.0	23.9	26.2	28.3	30.2	31.9	33.7	35.4	37.1	38.8	40.6	42.6	44.7	47.0	49.7
PPM discharge allocation (gBODu/s)																	
2. Pope & Talbot	38.6	70.3	87.6	99.7	109.4	118.0	125.8	133.3	140.5	147.6	154.7	162.0	169.6	177.7	186.5	196.2	207.5
3. James River	5.5	10.1	12.5	14.3	15.7	16.9	18.0	19.1	20.1	21.1	22.1	23.2	24.3	25.4	26.7	28.1	29.7
6. Willamette Ind	16.8	30.6	38.2	43.4	47.7	51.4	54.8	58.0	61.2	64.3	67.4	70.6	73.9	77.4	81.2	85.4	90.4
9. Smufit (Newberg)	26.0	47.4	59.1	67.2	73.8	79.6	84.8	89.9	94.7	99.5	104.3	109.2	114.4	119.8	125.7	132.3	139.9
12. Smufit (Oregon)	95.4	173.7	216.6	246.4	270.5	291.7	311.1	329.4	347.2	364.8	382.4	400.5	419.3	439.3	460.9	485.1	513.0
13. Simpson	16.8	30.5	38.1	43.3	47.5	51.3	54.7	57.9	61.0	64.1	67.2	70.4	73.7	77.2	81.0	85.3	90.2
% Reduction	0.82	0.67	0.58	0.53	0.48	0.44	0.40	0.37	0.33	0.30	0.27	0.23	0.20	0.16	0.12	0.07	0.02
Total Discharge (gBODu/s)	352	640	799	908	997	1075	1147	1215	1280	1345	1410	1477	1546	1620	1700	1788	1891
Total Savings (1999 $mil/yr)	56.7	83.3	92.2	96.9	100.1	102.6	104.9	107.1	109.2	110.9	112.3	113.6	114.7	115.9	117.1	118.4	119.9
Total Cost (1999 $mil/yr)	86.1	59.5	50.6	45.9	42.7	40.2	37.9	35.7	33.6	31.9	30.5	29.2	28.1	26.9	25.7	24.4	22.9

Table C-2: After-trading wasteload allocation and cost figures for the Willamette River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
WWTP discharge allocation (gBODu/s)																	
1. Metropolitan	10.0	20.0	32.4	32.4	32.4	65.2	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9
4. Corvalis	4.2	8.3	13.5	13.5	13.5	13.5	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8
5. Albany	3.7	7.3	11.9	11.9	11.9	11.9	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5
7. Salem	29.0	29.0	57.9	78.0	93.9	93.9	93.9	93.9	93.9	93.9	93.9	93.9	93.9	99.6	179.4	193.7	193.7
8. Newberg	2.1	3.4	3.4	3.4	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
10. Wilsonville	1.5	4.9	4.9	4.9	4.9	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
11. Canby	2.0	2.0	2.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
14. Tri-City	5.2	10.5	17.0	17.0	17.0	17.0	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1
15. Portland	50.2	60.0	92.0	120.1	189.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	269.3	372.2
16. Oak Lodge	1.8	5.9	5.9	5.9	5.9	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
17. Clackamas	6.0	15.1	15.1	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	50.5	50.5	50.5	50.5	50.5
PPM discharge allocation (gBODu/s)																	
2. Pope & Talbot	78.7	157.4	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7
3. James River	20.6	20.6	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2
6. Willamette Ind	34.8	85.9	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8
9. Smufit (Newberg)	15.4	92.1	92.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1
12. Smufit (Oregon)	55.3	55.3	55.3	55.3	55.3	55.3	80.1	147.8	213.3	278.1	343.2	409.8	453.1	521.0	521.0	521.0	521.0
13. Simpson	31.3	62.7	62.7	62.7	62.7	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6
Total Discharge (gBODu/s)	352	640	799	908	997	1075	1147	1215	1280	1345	1410	1477	1546	1620	1700	1788	1891
Total Savings (1999 $mil/yr)	72.8	101.6	108.3	111.5	113.3	114.6	115.3	115.9	116.4	117.0	117.5	118.1	118.6	119.0	119.4	119.8	120.3
Total Cost (1999 $mil/yr)	70.0	41.2	34.5	31.3	29.5	28.2	27.5	26.9	26.4	25.8	25.3	24.7	24.2	23.8	23.4	23.0	22.5

Table C-3: Least-cost wasteload allocation and cost figures for the Willamette River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
WWTP discharge allocation (gBODu/s)																	
1. Metropolitan	19.2	32.4	32.4	32.4	56.7	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9	66.9
4. Corvalis	4.2	13.5	13.5	13.5	13.5	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8
5. Albany	3.7	11.9	11.9	11.9	11.9	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5
7. Salem	29.0	29.0	57.9	93.9	93.9	93.9	93.9	93.9	93.9	93.9	93.9	93.9	129.7	193.7	193.7	193.7	193.7
8. Newberg	2.1	3.4	3.4	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
10. Wilsonville	1.5	4.9	4.9	4.9	4.9	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
11. Canby	2.0	2.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
14. Tri-City	5.2	10.5	17.0	17.0	17.0	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1
15. Portland	60.0	60.0	120.1	155.4	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	194.6	199.4	280.9	374.8
16. Oak Lodge	1.8	5.9	5.9	5.9	5.9	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
17. Clackamas	7.5	15.1	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	50.5	50.5	50.5	50.5	50.5
PPM discharge allocation (gBODu/s)																	
2. Pope & Talbot	78.7	173.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7
3. James River	20.6	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2
6. Willamette Ind	34.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8	91.8
9. Smufit (Newberg)	15.4	92.1	110.5	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1	142.1
12. Smufit (Oregon)	55.3	55.3	55.3	55.3	55.3	71.3	136.6	198.2	257.9	316.7	375.8	436.1	443.1	453.4	521.0	521.0	521.0
13. Simpson	31.3	62.7	62.7	62.7	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6
Total Discharge (gBODu/s)	372	694	857	963	1056	1138	1204	1265	1325	1384	1443	1503	1572	1646	1719	1800	1894
Total Savings (1999 $mil/yr)	75.9	104.3	110.2	112.6	114.3	115.2	115.8	116.3	116.8	117.3	117.8	118.3	118.7	119.1	119.5	119.9	120.3
Total Cost (1999 $mil/yr)	66.9	38.5	32.6	30.2	28.5	27.6	27.0	26.5	26.0	25.5	25.0	24.5	24.1	23.7	23.3	22.9	22.5

Table C-4: Before-trading wasteload allocation and cost figures for the Athabasca River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.20	0.10
WWTP discharge allocation (tonBOD5/d)																	
1. Welwood	2.24	2.64	2.85	3.00	3.12	3.22	3.32	3.41	3.50	3.58	3.67	3.75	3.84	3.94	4.04	4.28	4.62
2. Alberta Newsprint	1.43	1.68	1.81	1.91	1.98	2.05	2.11	2.17	2.23	2.28	2.33	2.39	2.45	2.51	2.57	2.73	2.94
3. Millar	1.39	1.63	1.76	1.85	1.93	1.99	2.05	2.11	2.16	2.21	2.27	2.32	2.38	2.43	2.50	2.65	2.86
4. Alberta Energy	0.71	0.84	0.91	0.95	0.99	1.03	1.06	1.08	1.11	1.14	1.17	1.19	1.22	1.25	1.29	1.36	1.47
5. Alberta Pacific	3.06	3.59	3.89	4.09	4.25	4.40	4.53	4.65	4.77	4.88	5.00	5.12	5.24	5.37	5.51	5.84	6.30
Uni Discharge (kgBOD5/ADT)	2.04	2.40	2.59	2.73	2.84	2.93	3.02	3.10	3.18	3.26	3.33	3.41	3.49	3.58	3.67	3.89	4.20
Total Discharge (tonBOD5/d)	8.8	10.4	11.2	11.8	12.3	12.7	13.1	13.4	13.8	14.1	14.4	14.8	15.1	15.5	15.9	16.9	18.2
Total Savings (1979 $mil/yr)	17.7	20.3	21.7	22.7	23.5	24.2	24.8	25.4	26.0	26.5	27.1	27.6	28.1	28.7	29.3	30.0	31.0
Total Cost (1979 $mil/yr)	22.0	19.5	18.0	17.1	16.3	15.6	14.9	14.3	13.8	13.2	12.7	12.1	11.6	11.0	10.4	9.7	8.8

Table C-5: After-trading wasteload allocation and cost figures for the Athabasca River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.20	0.10
WWTP discharge allocation (tonBOD5/d)																	
1. Welwood	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.26	4.66	5.61	6.94
2. Alberta Newsprint	0.35	0.35	0.35	0.56	1.04	1.12	1.12	1.12	1.12	1.12	1.44	1.79	2.14	2.31	2.31	2.31	2.31
3. Millar	0.34	0.34	0.72	1.09	1.09	1.09	1.20	1.55	1.90	2.23	2.24	2.24	2.24	2.24	2.24	2.24	2.24
4. Alberta Energy	0.56	0.56	0.56	0.56	0.56	0.89	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
5. Alberta Pacific	3.52	5.07	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54	5.54
Total Discharge (tonBOD5/d)	8.8	10.4	11.2	11.8	12.3	12.7	13.1	13.4	13.8	14.1	14.4	14.8	15.1	15.5	15.9	16.9	18.2
Total Savings (1979 $mil/yr)	19.2	22.5	24.2	25.3	26.2	26.7	27.1	27.4	27.7	28.0	28.3	28.6	28.9	29.2	29.6	30.4	31.5
Total Cost (1979 $mil/yr)	20.6	17.2	15.5	14.4	13.5	13.0	12.6	12.3	12.0	11.7	11.4	11.1	10.8	10.5	10.2	9.4	8.3

Table C-6: Least-cost wasteload allocation and cost figures for the Athabasca River for the DO concentration standard of 5 mg/L

Before-Trade Reliability	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.20	0.10
WWTP discharge allocation (tonBOD5/d)																	
1. Welwood	1.54	2.37	2.89	3.28	3.62	3.79	3.95	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.81
2. Alberta Newsprint	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94	2.94
3. Millar	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.13	1.30	1.48	1.65	1.82	2.00	2.19	2.24	2.24	2.24
4. Alberta Energy	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47	1.47
5. Alberta Pacific	5.54	5.54	5.54	5.54	5.54	5.71	5.90	6.09	6.31	6.54	6.79	7.05	7.34	7.67	8.18	9.60	11.07
Total Discharge (tonBOD5/d)	12.6	13.4	13.9	14.3	14.6	15.0	15.3	15.7	16.1	16.5	16.9	17.3	17.8	18.3	18.9	20.3	22.5
Total Savings (1979 $mil/yr)	23.0	24.9	26.0	26.9	27.6	28.1	28.6	29.1	29.4	29.7	30.0	30.4	30.8	31.2	31.7	32.8	34.5
Total Cost (1979 $mil/yr)	16.7	14.9	13.7	12.9	12.1	11.6	11.1	10.7	10.4	10.0	9.7	9.3	9.0	8.5	8.1	7.0	5.2