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Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River

Volume 1: Planning guidelines

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Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River

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Environmental Protection Branch
Environment Canada – Quebec Region
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Foreword

This document is intended to help proponents and managers of dredging and marine engineering projects to design and implement sediment sampling plans that satisfy concerns about the physical and chemical characterization of sediments. The guidelines are accompanied by explanations and advice, to enhance the guide's efficiency.

This guide also complements the bioassay methods published by Environment Canada for toxicity and bioaccumulation tests on pore water and whole sediments. The standardized approaches and operating methods suggested here must be followed to ensure the standardization of procedures for sample collection and the documentation of characterization work. This will facilitate successful sampling and improve the acceptability of results.

The use of this guide for sampling operations for sediments dredged from the St. Lawrence River is recommended by Environment Canada, the Quebec Environment ministry, Fisheries and Oceans Canada, Transport Canada, Public Works and Government Services Canada, and the Société de la Faune et des Parcs du Québec (Quebec Wildlife and Parks Corporation).

Abstract

The approach used to characterize sediments in dredging and marine engineering projects has been revised and updated in a new two-volume methods manual. The first volume, *Planning Guidelines,* is intended for planners of characterization studies, while the second volume, *Field Operations Manual*, is addressed to the technical teams carrying out the sampling work. The use of this guide is recommended to ensure the standardization of procedures for collecting samples and documenting sediment characterization work.

This volume is divided into four chapters. The introduction describes the relevance of the guide and the context in which it was written in order to define the constraints involved in carrying out characterization studies in a standardized framework. The second chapter introduces the principal objective of sediment characterization studies, which is to obtain samples in order to characterize sediments from dredging, disposal and reference sites; in addition, a number of factors that may affect the informational value of the samples are discussed. The third chapter deals with the planning of sampling operations, including the development of a specific sampling approach and study design for the project. The main components of a study design are described by explaining how to use the available information and data to determine the sampling strategy, type of sampler to be used, rules for handling and preserving samples, and some general aspects of logistics and health and safety that may affect the implementation of a sampling campaign. The fourth chapter deals with the quality assurance and control of sampling activities in a project. The various subjects to be covered are dealt with in a discussion on developing a quality assurance and control program, which all planners must take into account before carrying out a characterization study.

Résumé

L'approche de caractérisation des sédiments dans le cadre des projets de dragage et de génie maritime a été revue et mise à jour dans un nouveau guide méthodologique présenté en deux volumes. Le premier volume, intitulé *Directives de planification* est destiné aux planificateurs de l'étude de caractérisation alors que le second, intitulé *Manuel du praticien de terrain*, est destiné aux équipes techniques chargées des travaux d'échantillonnage. L'utilisation du guide méthodologique est recommandée pour assurer une normalisation des procédures de collecte des échantillons et de documentation des travaux de caractérisation des sédiments.

Le présent document est divisé en quatre chapitres. Dans l'introduction, on présente l'à-propos de ce guide ainsi que le contexte dans lequel il a été élaboré afin de définir les contraintes entourant la réalisation d'études de caractérisation dans un cadre normalisé. Le deuxième chapitre présente l'objectif principal de l'étude de caractérisation qui est d'obtenir des échantillons afin de caractériser les sédiments aux sites de dragage, de rejet et de référence (selon le cas), en considérant un certain nombre de facteurs qui affecteront la valeur informative des échantillons. Dans le troisième, on aborde la planification de l'échantillonnage qui recoupe l'élaboration d'un plan d'étude et d'une approche d'échantillonnage spécifique au projet. Les principales composantes du plan d'étude sont donc présentées en décrivant comment utiliser l'information et les données disponibles pour déterminer la stratégie d'échantillonnage, le type d'échantillonneur, les règles de manipulation et de conservation des échantillons et certains aspects généraux de logistique et de santé et sécurité pouvant affecter le déroulement d'une campagne d'échantillonnage. Dans le quatrième chapitre, il est question des aspects relatifs à l'assurance et au contrôle de la qualité des activités d'échantillonnage d'un projet. Les différents aspects à couvrir sont présentés dans le cadre de l'élaboration d'un programme d'assurance et de contrôle de la qualité que tout planificateur devrait considérer avant de réaliser une étude de caractérisation.

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Glossary

Accuracy: Accuracy is the degree of correspondence between an experimentally determined value and a recognized reference value. In practice, accuracy can be expressed in the form of deviation and recovery.

Chain of custody: Documentation certifying the possession (series of holders of the sample) of a sample from the collection to the analysis stage, to prove that it was neither falsified nor contaminated during this period.

Conceptual hydrodynamic and sediment model: Illustration of hydrodynamic and sediment conditions in a given sector based on the pattern of currents and the nature of the sediments. The purpose of such models is to identify areas of sediment accumulation, erosion and transport to assist in the selection of sampling station sites.

Control sediments: Uncontaminated sediments, either artificial (prepared in the laboratory) or taken in the field, of known physicochemical composition and consistent quality. They must not contain concentrations of contaminants that affect the test organism in any way. Their physical characteristics must be within the tolerance limits of the test organisms and they must be free from any organisms harmful to the test organism. Control sediments serve as a point of comparison for interpreting the results of toxicity and bioaccumulation assays on the test sediments. They can also be used to verify the health of the test organisms, the changes over time in the relative sensitivity of the test organisms, and the laboratory's analytical performance.

Corer: Type of sampler used to collect a vertical sample of sediments of a certain thickness inside a tube usually made of plastic.

Cross contamination: Cross contamination occurs when a sample from an uncontaminated or relatively uncontaminated station comes in contact with a sample from a more contaminated station. Proper cleaning of the various sampling instruments reduces the risk of cross contamination.

Data comparability and compatibility: Data comparability is based on the measurement of the degree of confidence with which one series of data can be compared to another; compatibility is based on the degree of accuracy and consistency characterizing the series of data to be compared (sampling, analysis, recording and processing of analog data, QA/QC data protocols, data increments, etc.).

Data quality indicator (DQI): Component of data quality that can be measured and described quantitatively.

Data quality objective (DQO): DQOs are descriptions of the measures to be taken if a piece of data does not conform to the desired results in terms of its specific application or use in decision-making. Examples: sampler penetration depth, sample volume, number of tests to be carried out before leaving a station, descent and ascent speed of sampler, etc.

Datum: Reference point from which calculations and measurements can be made.

Deep sampling: Sampling of sediments of a certain thickness using a corer. Generally, the thickness of the sample corresponds to the depth of dredging.

Deterministic sampling plan: Sampling plan in which the location of sampling stations is chosen by the person in charge based on specific criteria or based on the information available.

Disposal area: Sector having defined boundaries within which the excavated sediments will be dumped in open water.

Dredging area: Sector having defined boundaries within which sediments will be excavated.

Exploratory sampling: Sampling carried out before the main sampling campaign. The purpose is to obtain a minimum amount of information on the characteristics of the sediments in order to plan the sampling approach.

Grab sampler: Sampler with a set of jaws, which can be used to collect surface layers of sediment (generally less than 30 cm thick).

Homogeneous areas: Subzones or strata within the study area in which sediment characteristics are comparable.

Integral sample: Sample whose physicochemical properties are preserved during collection and handling.

Matrix: Set of fine sediments or materials that fill in the pores between pebbles or blocks. Each matrix is characterized by the size of the particles of which it is composed (e.g. silty, silty/gravelly or sandy-to-silty matrix).

Method detection limit (MDL): Minimum quantity or concentration of a substance that can be detected by the analysis method. It is the concentration equivalent to three times the standard deviation calculated from at least ten measurements of samples in which the concentration is as close as possible to the expected MDL. In selecting samples to determine the MDL, it must be taken into account that this value will only be valid if the ratio of the mean of *n* replicates to the MDL is between 4 and 10.

Physicochemical characterization: Set of analyses used to describe the nature of sediments, in terms of physical (particle size distribution, mineralogy, odour, etc.) and chemical (concentrations of organic and inorganic contaminants, organic matter, etc.) properties.

Pore water (syn.: *interstitial water)*: Water found in sediments. It occupies the space between the grains of the sediment matrix and is sampled in certain bioassays.

Precision: Indicates the agreement between the numerical values of two or more measurements, performed on the same homogeneous sample and under the same conditions. This word is used to describe the reproducibility of the measurement or method. It can be expressed as a standard deviation.

Preliminary site investigation: Site visit carried out before the beginning of work to familiarize the technical team with certain logistical aspects. During this visit, additional information can be obtained to finalize the sampling approach.

QA/QC program: See QA (quality assurance) and QC (quality control).

Quality assurance (QA): Designates an activity system whose goal is to provide the producer or user of a product (e.g. data) or service with the assurance that the product or service conforms to defined quality standards. It comprises two distinct but interrelated activities: quality control and quality assessment. The quality assurance process includes the documentation of methods, the identification of critical points in data collection activities that must be monitored using quality control methods, the level of quality obtained, the problems encountered, and the remedial measures undertaken.

Quality assurance plan: Document specific to a project or program, explaining the management structure, problems to be solved, data quality requirements and associated QA/QC (quality assurance/quality control) methods.

Quality control (QC): Designates an overall activity system whose goal is to control the quality of a product (e.g. data) or service in order to meet users' needs. The objective is to provide a degree of quality that is satisfactory, adequate, reliable and economical.

Random sampling plan: Sampling plan in which the location of sampling stations is randomly determined.

Recent stratigraphy: Information on the vertical distribution of sediments. It targets mainly the most recent accumulation of sediments to determine the type of material that will be encountered during sampling and dredging activity.

Recurrent dredging: Maintenance dredging done every one or two years.

Reference sediments: Sediments taken in the field and considered to be relatively free from contaminants (i.e. uncontaminated). Reference sediments are often taken near the site from which the test sediments come (i.e. in the same stretch of water) and are often used in toxicity assays since their geochemical characteristics (e.g. particle size distribution and total organic matter content) are similar to those of the test sediments. In toxicity assays, they can be used along with control sediments as a control.

Reference site: Site for sampling uncontaminated sediments in an environment with homogeneous characteristics that are comparable to those of the study area.

Representativeness and completeness: A value is representative when it can be used in calculations to replace one value or set of values. The representativeness of a sample is one of the key problems in research since a sample is by definition designed to be representative; the question is to know to what degree it is truly so. The representativeness of data is complementary to data completeness. Completeness is a factor that influences the validity of data. It is evaluated by measuring the quantity of valid data obtained using a measurement system and is expressed as a percentage of the number of valid measurements expected to be collected.

Representative sample: Sample whose characteristics allow data quality objectives to be met, particularly with regard to representation of the characteristics of the surrounding area.

Sample: Modest quantity of material taken for analysis and bioassay purposes.

Spiked control (or test) sample: Sediments to which a known quantity of toxic product has been added to obtain a specific concentration of the product in the sediments. These sediments can be used as a positive control to determine if, in time, the organisms tested react uniformly to a specific concentration of a reference toxic product. They can also be used to measure the effects that the sample matrix may have on analysis methods (usually on the recovery of the sought-after substance).

Standard deviation: Measurement of dispersion or spread of points corresponding to the data around a mean value that correspond to the data series obtained from repeated tests with a homogeneous sample under specific conditions. It is calculated from the square root of the variance of a series of values. In a more general sense, it corresponds to the measurement of the spread of points in any data series.

Standard operating procedure (SOP): Written document that details the methods for a sampling procedure, operation or action whose mechanisms are prescribed in great detail, and which is commonly accepted as the method for performing certain routine or repetitive tasks.

Station: Defined field site within the study and reference areas from which samples are taken.

Study design: Document that describes the proposed sampling approach for the study, including the sampling plan, sampling methods and the plan for analysing and interpreting the results.

Surface sampling: Sampling of the surface layer of sediments, generally less than 30 cm deep.

Systematic sampling plan: Sampling plan in which the location of sampling stations is determined with a grid so that the distance between sampling points is generally identical.

Whole sediments: Intact sediments that have undergone minimal handling after having been collected and prepared. Unlike an elutriate or resuspension, they are not a form or derivative of sediment.

1 Introduction

1.1 CONTEXT

Sediments are a fundamental component of ecosystems. They result from the deposition of terrigenous particles introduced into the aquatic ecosystem and precipitates formed from chemical and biological processes in the water column. Sediments are the site of many exchanges with the water mass and the complex biological and chemical processes occurring therein. The migration of particles towards the bottom and the formation of a more or less solid matrix can result in an increase in contaminant concentrations to often-high levels, depending on solubility, organic matter content and particle size distribution. Sediments therefore must be considered a reservoir or source of contaminants if they are resuspended or transferred to the food chain through predator-prey interactions.

Characterization studies are intended to respond to stakeholders' concerns regarding the protection of the integrity and health of aquatic ecosystems. Different methods for sampling sediments and pore water can be used to carry out physicochemical characterizations or ecotoxicological assessments or to measure bioaccumulation to respond to these concerns. The activities that these studies entail, however, are likely to influence the integrity of the physicochemical properties of sediments and consequently the results of the analyses. The purpose of developing standard operating procedures (SOPs), therefore, is to allow comparable results to be produced from different sampling campaigns.

This guide should help planners to use sampling approaches that are better adapted to the characteristics of the environment targeted by their projects, while incorporating the basic rules and principles of quality control and assurance.

1.2 SCOPE OF DOCUMENT

This first volume presents guidelines and general observations on developing a study methodology, including the choice of a sampling plan. It is intended for project planners who must establish a representative sampling approach. This is an important step in the process since the selection of sampling stations and methods for collecting, transporting, handling and storing samples can influence the results of analyses and toxicity assays.

The purpose of the guide is to define the requirements involved in the planning and execution of characterization studies in an integrated and standardized framework. Every project will involve special conditions, however, and the sampling approach used must be specifically adapted to the environmental conditions, taking into account the information available and dredging project objectives.

The second volume, which gives complete information and instructions on carrying out sampling operations, is to serve as a framework for developing operating procedures adapted to the specific characteristics of each project. It is intended mainly for technical personnel and provides a framework for using methods for sample collection, handling and storage.

Readers are also invited to consult the references used in drafting this document for more in-depth information on certain areas: IJC (1988), Baudo *et al*. (1990), Environment Canada (1994), USEPA (1994, 2000), ASTM (1997), Mudroch and Azcue (1995), USEPA/USACE (1998a, 1998b).

2 Sampling Campaign

The primary objective of a sampling campaign is to obtain adequate samples for the physicochemical and ecotoxicological characterization of sediments at a dredging site and, depending on the case, at disposal or reference sties. Certain factors, which are essential and inherent in achieving the specific objectives of each study, can also affect the informational value of the samples. They include:

- Sample representativeness
- Sample integrity
- Sufficient number of samples
- Appropriate sampling techniques
- Adequate techniques for preserving samples until analysis.

The success of a sampling campaign depends on detailed planning emphasizing the development of flexible scenarios to deal with unforeseen conditions in the field and the nature of the sediments found. This is particularly true for projects where little information is available. The results are incorporated into the design of the sediment characterization study, which, as Figure 2.1 shows, consists of a number of stages such as developing objectives, planning, field testing, laboratory analyses and reporting.

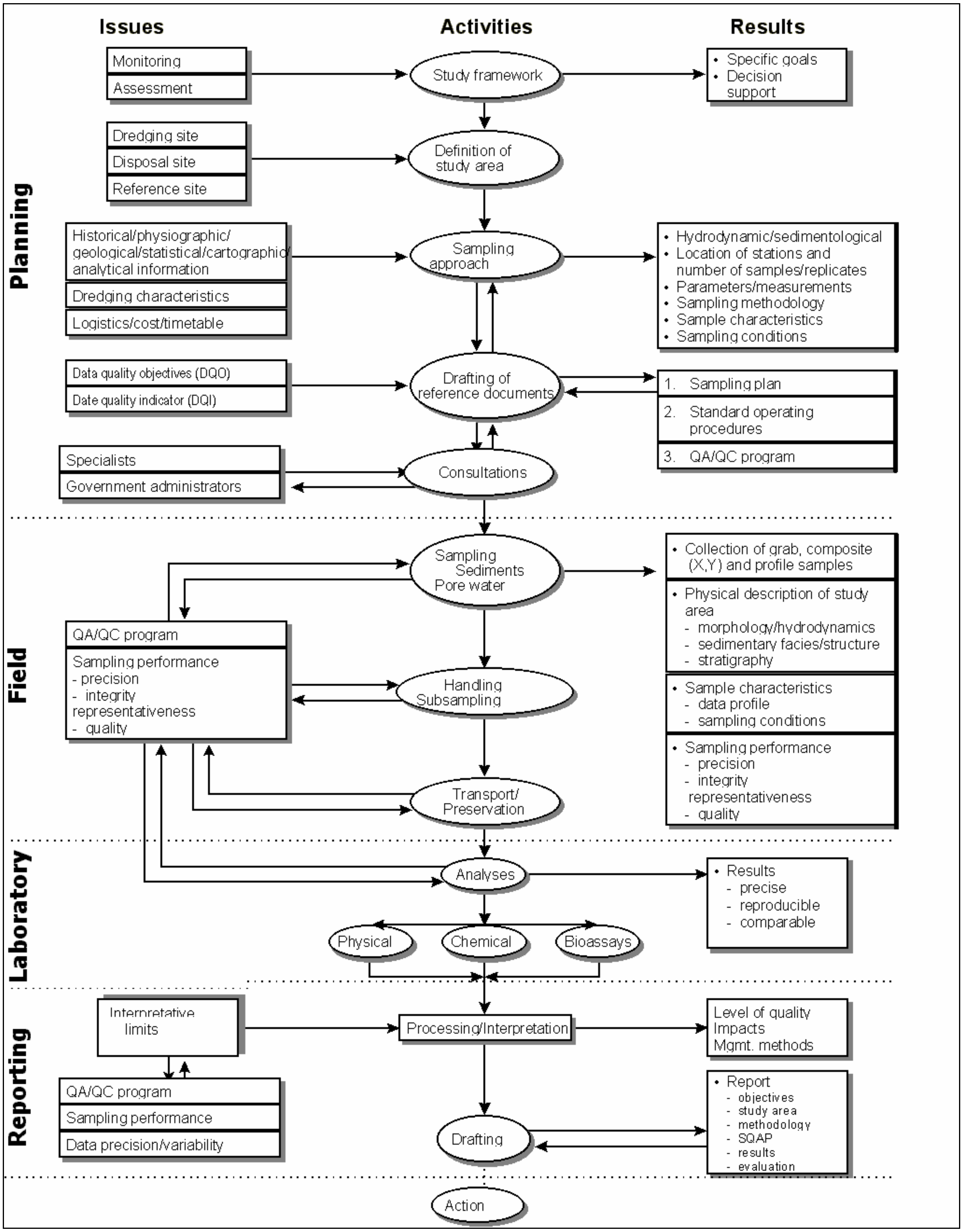

Figure 2.1 **Flow chart of a sediment characterization study**

3 Planning of Sampling Operations

3.1 OVERVIEW

The planning of sampling is essential to ensuring the quality of the results of the chemical and biological analyses, in terms of meeting the objectives for representativeness. Although there are boilerplate methods for planning sampling operations, specific circumstances always come into play and must be taken into account when devising a plan.

Factors affecting the quality of samples, and intrinsically their informational value, must be carefully taken into account (USEPA/USACE 1998b). According to Håkanson and Jansson (1983), roughly a dozen factors can affect the informational value of a sample, and although there is no technique for integrating them systematically, the sampling approach used must attempt to maximize the information generated from each sample by taking these factors into account. The factors are shown in Table 3.1.

Most of the factors shown in the table are different at each site and the overall study design must incorporate these elements by using an approach adapted to each one. Although the main techniques used in this adaptation process are described in this guide, planning must also be done in a more general framework. Therefore, it is recommended that a document describing the sampling approach be drawn up for every study. The document should include such things as the design of the sampling plan, the type of samplers and methods to be used and methods for handling samples. The document will include the main components of the study design and a quality assurance and control program (see the next section for more information).

Table 3.1
Factors affecting the informational value of samples

1	Aquatic system	Identify the hydrodynamic processes and adapt the sampling plan accordingly (direction of flow, stratification, etc.)
2	Sediment dynamics	Zones of sediment erosion, transport and accumulation defined based on hydrodynamic processes, distribution of beds of aquatic vegetation, etc.
3	Size of study area	Factors 3 and 4 are used to determine the number of stations. Different approaches (statistical, random selection) can be used. The final approach must take account of sampling costs.
4	Number of samples	
5	Substrate relief	The interval used in the sampling grid must take account of the morphology of the study area (presence of shoals, channels, basins, etc.).
6	Anthropogenic sources	The sampling plan must take account of nearby sources (i.e. within the study area).
7	Geochemistry (O_2, Eh, pH)	The sampling period selected must take account of seasonal variations in sediment characteristics where applicable.
8	Physical and biological characteristics of sediments	The sampling depth must correspond to the depth of the mixed layer (resulting from reworking by biophysical processes) or homogeneous layers.
9	Sampling approach	To be defined based on historical data, knowledge of the environment and previous work.
10	Quality of sampler	The sampler characteristics must be known and its performance documented.
11	Subsampling	Systematic (0-15 cm without contact with liner, if possible) and adapted to reflect chemical analyses (plastic or metal depending on the circumstances)
12	Quality of chemical analyses	A quality control program must be set up.

(Håkanson and Jansson, 1983)

3.2 ANALYSIS PARAMETERS

Determining the parameters to be analysed is a critical part of planning a sampling campaign. With the significant cost of chemical analyses, wise choices are required in each case. Tables F.1, F.2 and F.4 (Appendix F) of volume II (*Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River: Field Operations Manual)* show the main parameters used for sediments and pore water. Documents such as *Interim Criteria for Quality Assessment of St. Lawrence River Sediments* (1992) and *Méthods Manual for sediment Characterization* (1993) also provide suggestions on the parameters to be analysed and on analysis methods.

3.3 COMPONENTS OF SAMPLING PLAN

The sampling plan must include the components shown in Table 3.2 as well as a quality assurance and control program (QA/QC program). An iterative process is used to draft the document. The objective is to adapt the sampling plan not only to statistical and scientific considerations intrinsic to the study but also, and equally as importantly, to the logistical and budgetary constraints inherent in any dredging project. The plan is then submitted to the clients and representatives of the government departments involved for discussion and approval.

Table 3.2
Main components of a sampling plan for sediment characterization studies

Objectives	Definition of study objective and initial hypotheses
Review of available data	1. Review of dredging program ▪ area ▪ target depth ▪ volume dredged taking account of side slopes ▪ dredging method 2. Description of current state of environment (historical information) ▪ Sediment contamination ▪ types of contaminants - concentrations - data quality (relevance, completeness, detection limits, precision) - identification of areas of potential interest ▪ Physical and geological conditions - bathymetry - water level variations (tides, flow rate, floods, low water, etc.) - hydrodynamic processes (wave and current regimes) - stratigraphy and nature of recent and older sediments - general information on drainage pattern (stream and river sites) ▪ Development of a conceptual hydrodynamic and sediment model
Sampling plan	1. Subdivision of study area (dredging area only) □ into strata (Environment Canada 1994) □ into management units (Mudroch and MacKnight 1994, USEPA/USACE 1998a) 2. Sampling strategy 3. Sampling effort 4. Positioning of stations 5. Choice of sampling equipment 6. Handling, preservation and storage of samples 7. Logistics

This plan will serve as a reference document during the actual sampling campaign and will be updated to reflect the results of the quality assurance and control component, consisting mainly of a description of the sampling conditions and elements related to performance measurements. Finally, the document will be incorporated into the technical study report.

The following sections provide additional details on the various aspects of the sampling plan.

3.3.1 Review of available data

3.3.1.1 Review of dredging program

The formulation of the sampling plan begins with research on the dredging project and the integration of the information:

- The boundaries of the dredging and sediment disposal areas are used to determine the number of samples to be collected, and their location in relation to the areas affected by the work;
- The volume of material to be excavated and excavation depth are essential pieces of information to determining the minimum number of samples to be collected (see Section 3.2.5) and the strata to be subsampled; this will also depend on the dredging method.

3.3.1.2. Description of current state of environment (historical information)

The compilation of available historical information helps in designing a sampling plan that is the most representative possible and in defining the optimum sampling methodology. The information to be gathered includes:

- Identification of zones that are homogeneous in terms of their physicochemical characteristics, in order to target areas of accumulation of fine and contaminated sediments and thus to more effectively determine the location of the sampling stations.
- Identification of the contaminants present (to optimize the analysis plan).
- Identification of the sources of contamination within the study area in order to guide the sampling plan accordingly.
- Description of the nature of the sediments and thickness of sediment deposits in order to better determine what sampler or samplers are to be used.

More specifically, the historical information reviewed should include the following:

Physical and chemical data. A description of the physical and chemical conditions present at the work sites entails doing an examination of geochemical data, of the local stratigraphy and of the hydrodynamic and hydrological conditions. This information, combined with various observations on the nature of the sediments (particle size distribution, specific density, water and organic matter content), will allow the sampling plan to be targeted more effectively, ensuring that a sufficient number of stations in the study area are included. For example, if the sediments to be excavated include uncontaminated Quaternary sediment deposits, the sampling and analysis effort can be reduced.

The description of the physicochemical characteristics of the sediments will also be used to select a specific sampler and, in some cases, to determine if collection methods need to be optimized by using a few different types of samplers. The choice of a sampler also depends on the objectives of the study. A grab sampler can be used in some sectors while others will require a corer, which can sample at greater depth (see Section 3.2.6).

Changes in hydrodynamic and sedimentological conditions can lead in turn to significant changes in the particle size distribution of surface sediments (e.g. areas of silt, sand or gravel). In such cases, the development of a conceptual hydrodynamic and sedimentological model (not to be confused with a digital model) may be beneficial. This model is a cartographic and geographic representation of hydrodynamic and sedimentological conditions based on the interpretation of the available data on the nature of the sediments and hydrodynamic conditions such as currents, waves, tides and seasonal variations in flow rates (flood, low water). The purpose of developing such a model is to determine areas subject to sediment erosion, transport and accumulation and to determine seasonal variations in the nature of sediments, in order to develop a more precisely targeted sampling plan.

In principle, conceptual modelling is used mainly for large-scale projects or those that have a significant geographic scope and in which the hydrodynamic conditions and nature of the sediments may vary spatially.

Developing a hydrodynamic and sedimentological model

In general, the spatial distribution of contaminants in an aquatic environment corresponds to the distribution of the physical characteristics of the sediments. Notwithstanding the multitude of conditions that may exist in an aquatic environment, it is recognized that the highest concentrations of contaminants are associated with areas of fine sediments (< 63 μm) that also have high concentrations of organic carbon. Fine-grained sediments usually accumulate in low-energy zones such as bays, basins and deep areas, while coarse sediments such as sand and gravel are found at the bottom of fast-flowing channels and shallow areas subject to certain hydrodynamic processes (waves, currents, tides, etc.). Consequently, interpreting the hydrodynamic and sedimentological context of the study area is crucial to developing a sampling approach.

A conceptual model of the hydrodynamic and sedimentological context of the study and disposal areas should be based on the following information, when available:

- Hydrodynamic conditions (tides, currents, wave and swell regime, flow rate)
- Sources of sediments and seasonal variations
- Recent stratigraphics (depending on scale of dredging project)
- Sediment erosion and accumulation rates
- Hydrological data (e.g. presence of fresh and salt water, which affect the concentration of suspended matter and metal absorption/desorption processes).

In some cases, when no information is available, a preliminary site visit will be required to carry out preliminary sampling or at least to do a visual observation of the substrate.

The degree of refinement of, and effort invested in, the model will depend on the information available and the context of the dredging project.

Quality and age of historical data. Before the historical data can be incorporated, the value and quality of the data must be adequately assessed. Quality data on the nature of the contamination will lower study costs by allowing analyses to be more precisely targeted. On the other hand, the elimination of parameters that are usually analysed must be justified, either by historical results documenting the absence of contamination by these parameters or by a review of local anthropogenic activities demonstrating the absence of known sources.

If the historical data do not meet current quality control standards, they can still be useful in a more qualitative context. In addition, a compilation of historical data should allow shortcomings in previous characterization studies to be identified so they can be remedied.

Anthropogenic factors and incidental releases. Historical data must also be examined to identify and locate the main sources of contamination, as well as any accidental discharges that could affect sediment quality in the study area. This information will allow a more accurate assessment of the sampling effort required so that there are a sufficient number of sampling stations in the sectors in question.

History of dredging. The purpose of a review of previous dredging studies is to optimize the sampling approach and assist in the choice of sampler. This information can be very influential in the development of a sampling approach.

In areas subject to recurrent dredging and where sediments are subject to intensive mixing by waves, currents or the wakes of ships, sediment deposits tend to be homogeneous due to repeated cycles of resuspension and settling. In this case, only surface sampling with a grab sampler will be needed, rather than deep sampling using a corer.

Chemical data from previous studies can also be used to identify areas that should be subject to a greater sampling effort (USEPA 1994) and to determine the contaminants to be studied in order to optimize the analyses. If no information is available on the vertical distribution of contaminants, a deep sampling (using a corer) of the entire sediment column targeted for dredging would be justified.

Knowledge of the thickness of the sediment column and the projected depth of dredging can also be used to identify the type of sampler required (grab sampler or corer) and whether core subsampling is needed. In some cases, sediments below the expected depth of dredging will have to be sampled if the expected dredging depth is less than the depth of the potentially contaminated surface deposits. This will ensure that the sediment exposed after dredging will be less contaminated than the dredged materials.

3.3.2 Sampling plan

3.3.2.1 Subdivision of study area

Sediment characteristics usually vary within the boundaries of the dredging area according to geographic, hydrodynamic and bathymetric conditions as well as the location of contaminant sources. Therefore, it is crucial to tailor the sampling strategy and effort so that spatial variability is accurately described.

The proposed approach entails stratifying the study area into homogeneous zones with comparable physicochemical characteristics. Subsequently, the sampling interval[1] and analysis program should be adapted by maximizing the effort (number of stations, number of parameters to be analysed) in the most highly contaminated sectors. Sectors that are free from contamination or that contain coarse deposits that are usually less contaminated must also be sampled, but the number of stations and/or parameters to be analysed can be reduced. Analysis costs can also be minimized by:

- analysing all parameters at only some stations and a reduced number of parameters at all other stations[2]
- using a sequential approach in which the results from a first series of samples are interpreted to determine the need to analyse the next series of samples.

As a general rule, it is preferable to maximize the number of sampling stations, even if this means keeping samples in reserve for future use. This approach is more cost-effective than having to return to the site and take additional samples when there are not enough data.

Along with the horizontal subdivision, the study area should also be subdivided vertically based on the nature and thickness of the sediments. When contamination is found to be vertically stratified, the surface sediments can be divided into layers to correspond to the minimum excavation depth of the dredging equipment to be used.

The vertical subdivision of the dredging area is usually not required in the case of homogeneous sediments. In addition, a vertical subdivision of less than 0.5 m is usually excessive and not justified owing to the dredging accuracy of dredging equipment.

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[1] Sampling interval: Distance between two sampling points on a systematic grid.

[2] Unless there is a high covariance between all the parameters, this approach makes interpreting the results more difficult.

Readers should also note that several horizontal and vertical subdivisions may be required in large-scale dredging projects in environments affected by industry, due to the area and volume of sediment involved. The greater the heterogeneity of the study area, the greater the number of sampling stations required. If sediment distribution is fairly uniform and contaminant levels are low, the study area may not have to be subdivided. Lastly, if the amount of information available varies, sectors that are less well documented should be subdivided into smaller areas to determine if pockets of contamination are present.

In addition, subdividing the dredging area into smaller plots means that smaller volumes of sediments will have to be dealt with, allowing sediments to be managed more efficiently and thus reducing management costs.

It is also important that the sampling program be sufficiently flexible to allow modifications to be made during the actual work to correspond to observations made in the field. In addition, additional sampling may be required to clear up uncertainties raised during the main characterization campaign (CCME 1993).

a) Preliminary site investigation

When no documents on the history of the site are available, a preliminary site investigation has a number of advantages. It allows gaps in knowledge on such things as the nature of sediments and the location of contaminated areas to be filled in, in order to finalize the sampling plan. It also allows the person in charge of the field campaign to identify any potential dangers in terms of sampling conditions (currents, structures, debris on the bottom, etc.) and to plan remedial measures.

During the site investigation, the goals are to:

- ask the client or resource people (local interest groups, Quebec Environment ministry, Environment Canada, Fisheries and Oceans Canada, Coast Guard) about previous activities in the study area
- obtain information on the dredging and sediment disposal areas (previous dredging, frequency, volume, types of dredges used, disposal areas)
- inspect the site (using the protective equipment required according to site health and safety rules), which involves taking photographs, noting access (boat launch, berths, anchorages), identifying potential locations for field laboratory (where required), identifying sources of electricity and water, etc.

- obtain information on shipping traffic that may impede sampling work (shipping lanes, schedules)
- observe currents, depths and types of sediment.

The information obtained must be incorporated quickly to allow the sampling approach (sampling plan, choice of samplers, subsampling effort, logistics, etc.) to be fine-tuned before the field team arrives on the site to begin work. Observations on the physical environment can be made from a boat (samples can be taken by grab sampler, the site can be examined by divers or photographs can be taken with an underwater camera to visualize the substrate characteristics). Underwater observations can be used to assess the degree of sediment consolidation and the presence of debris, thus facilitating the choice of a sampler. In the presence of extremely turbid conditions or obstacles, geophysical methods such as acoustic sounding (echosounding, seismic reflection, side-looking sonar, etc.) allow indirect observations of sediment deposits to be made.

b) Exploratory sampling

When no historical information is available on the type and level of contamination, and when a statistical approach is to be used to determine the number of sampling stations, exploratory sampling may be required, particularly if a high level of contamination is suspected. Acoustic sounding combined with physical analyses such as particle size distribution and TOC can be used to identify strata with homogeneous characteristics. Such exploratory sampling should make up roughly 10–15% of the entire study effort. The preliminary data obtained must also be analysed before the main sampling campaign can proceed. It is crucial to use the same protocols for the exploratory sampling and analyses as those used for the main sampling campaign.

If results come from different stations, there may be a spatial correlation in the data on contamination. The presence of fairly consistent contaminant concentrations from station to station is less common than concentrations that vary widely. Generally, spatial correlations in concentrations can be observed: in other words, there is a progressive increase (or decrease) in contaminant concentrations beginning at a particular point (for example, a discharge point). Such spatial trends have a direct impact on the results of variance calculations, increasing the variance.

Most statistical analysis methods require that data be uncorrelated. Therefore, beginning at the sampling stage, any correlation that occurs must be eliminated or must be taken into account by using statistical methods that allow it to be measured.

Figure 3.1 shows how correlation can be eliminated beginning at the sampling stage. It shows a systematic grid consisting of nine sections. Contaminant concentrations, shown by the shading of each section, increase progressively from bottom to top. Concentrations do not vary horizontally, however. The individual sampling of sections 1, 2 and 3 will result in a high degree of variance due to the trend. On the other hand, taking samples from a mixture of sections of 1, 2 and 3 will completely eliminate the effect of the trend. In this hypothetical illustration, a null variance could be obtained by taking three samples from sections 1, 2 and 3, moving horizontally.

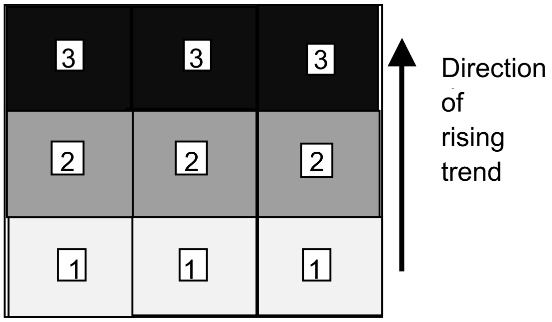

Figure 3.1 Sampling using a systematic grid to eliminate correlation beginning at the sampling stage

Readers should note that it is not necessarily desirable to eliminate correlation, particularly at the exploratory stage, since the identification of trends often provides indispensable information on the location of the most contaminated sectors, as well as the potential location of areas free from, or with negligible, contamination. The approach recommended in this guide is to gather information at the various stations first, which allows any pattern in the spatial distribution of contaminants to be ascertained.

When a trend is present, the variance in the results will have two components: the sampling variance and the variance caused by the presence of the trend. Only the sampling variance is representative of the random errors in the sampling process. This variance results from the sum of the different sources of variation in the sampling process such as sample collection, homogenisation (in the field), subsampling (in the laboratory) and analysis. In practice, these are the only sources of variation that can be controlled. Improving sampling and analysis techniques in order to better control the causes of variation must be a primary objective in any sampling campaign. For example, in the case of solid samples, variance can often be reduced significantly by crushing the samples (Gy's theory). In addition, several statistical techniques can be used to distinguish sampling variance from correlation. Linear regression is the main method used for dealing with this problem (Gilbert 1987). This parametric method requires a normal data distribution; another requirement is that the variance be constant regardless of the concentration of contaminants. In practice, however, environmental data are typically heteroscedastic: in other words, variance increases as concentration does. Gilbert discusses several other techniques, including nonparametric methods and methods using an ARIMA-type moving average, to deal with this issue.

Multivariate analysis (Tabachnick et al. 1996) and geostatistics can also be used. Gy (1992) developed an approach that takes account of both trends and cyclical variations but also requires a large amount of data. In short, the usefulness of a given method depends on the statistical properties of the data, the level of thoroughness required in information processing, the availability of calculation software and financial considerations.

3.3.2.2 Sampling strategy

a) Dredging area

Several types of sampling plans can be used to study sediments. The type chosen will depend on the characterization objectives and the availability of historical information. In the case of dredging and marine engineering projects, the goal usually is to identify as accurately as possible the geographical boundaries of contaminated areas and the highest levels of contamination in order to determine adequate sediment management methods that will minimize the potential environmental impact as well as management or processing costs.

A well-prepared sampling plan will optimize data analysis and the interpretation of results. In addition, a sufficient sampling effort must be deployed to produce valid results and obtain an accurate statistical interpretation.

There are three basic types of sampling plans: deterministic, random and systematic (Figure 3.2). The basic types can be combined, however, resulting in varieties such as stratified random sampling (Environment Canada 1994, Mudroch and MacKnight 1994, Atkinson 1985), random systematic sampling, and deterministic systematic sampling.

Deterministic sampling plan. With this type of plan, station location is determined by the planner, based on the available information. The planner will choose one or more criteria for selecting station location such as the proximity of a discharge point or the presence of a specific type of sediment.

The objective of this type of plan is often to evaluate sectors with fairly high levels of contamination and usually insufficient information is obtained to properly characterize the entire dredging area. In addition, this type of plan does not lend itself as well to statistical inference (attributing properties found in samples to an entire area). This type of plan can only be used when there is sufficient information to justify the position of the stations. It is mainly used, therefore, in exploratory sampling.

Random sampling plan. In random sampling, station location is chosen at random, which allows the unrestricted use of statistics in processing the data. In general, simple random sampling is not recommended since the random techniques used to determine the location of stations lead almost inevitably to the non-uniform distribution of stations throughout the site. In other words, some sections are undersampled, while others are oversampled. In addition, if a trend is present (increased or decreased concentrations), it is always better to adjust the direction of sampling to correspond to the presumed direction of the trend.

The use of a random sampling plan can be optimized, however, by dividing the study area into homogeneous strata and randomly distributing sampling stations among the previously defined strata. In this way, a certain number of stations can be ensured in each stratum and the entire contaminant gradient in the study area can be properly characterized (Elliott 1983).

Strata are subdivided using a square or triangular grid (the latter has advantages when geostatistical interpolation techniques are used in data analysis). The location of the station in each square or triangle is determined by using a random number table, with the number of squares or triangles greater than the number of stations.

Systematic sampling plan. In systematic sampling, sampling stations are distributed regularly and at equidistance, generally using a square grid oriented along a given axis such as the direction of flow of a river or the direction of the residual current (tide). This type of sampling is useful since the entire area subject to a specific constraint or common condition is covered. On the other hand, the sampling effort is identical everywhere, so that the information provided by stations in some homogeneous sectors quickly becomes redundant. Therefore, there is a risk of deploying unnecessary sampling effort.

This type of sampling can be optimized by stratifying the study area into homogeneous strata according to sediment characteristics. Then a variable sampling interval is applied, with a smaller interval (more intensive sampling) in the most contaminated sectors or sectors with fine sediments.

Stratification should not be used, however, when the factors governing sediment distribution are already known. When no information is available, a grid is used. In harbour areas, bays, basins and areas sheltered from the main current can be considered as homogeneous strata in the sampling plan.

b) Disposal areas

If open-water disposal is being considered as an option for dredged materials, the sediments in the disposal area must also be characterized to ensure that contaminant concentrations in the excavated sediments do not exceed concentrations in sediments in the disposal area. The objective is to characterize surface sediments at the disposal site to compare them with the material that will form the surface after disposal. To do this, surface sampling of the disposal site is carried out, usually with a grab sampler. Sampling stations are usually selected randomly within the geographic boundaries of the disposal area. Stations must be defined by the project manager.

c) Reference site

The approach used in Quebec to evaluate sediment quality in dredging projects can involve as many as two characterization stages, depending on the degree of sediment contamination: physicochemical characterization and a toxicological assessment of sediments or pore water. The second stage is required when the level of contamination exceeds the minimal effect threshold (level 2), as set out in the *Interim Criteria for Quality Assessment of St. Lawrence River Sediments* (Environment Canada and MENVIQ 1992). In this case, a series of bioassays must be carried out to assess the impacts on the benthic fauna.

Bioassays require sampling the sediments at one or more reference sites.[3] If the sediments at the dredging site consist of materials with homogeneous properties, only a single reference site need be sampled. The reference sediments are then subjected to the same battery of tests and analyses as the sediments in the study area. However, if the sediments in the dredging area are heterogeneous (in terms of particle size distribution and/or organic matter content), comparable sediments may have to be sampled at different reference sites. The reference site must not be exposed to discharges affecting the dredging area and must not correspond to current or former disposal areas for sediments from previous dredging operations. Depending on the context of the study, reference samples can be analysed independently or combined in a composite sample.

In principle, reference sediments must be free from contamination and have the same basic properties (particle size distribution, organic matter content and other physical properties) as the sediments at the dredging site. In practice, it may be difficult to find sediments with similar basic properties; in this case, reference sediments can be taken from a slightly contaminated site (i.e. with contaminant concentrations equivalent to regional background levels). The physical characteristics of the reference site must be comparable to

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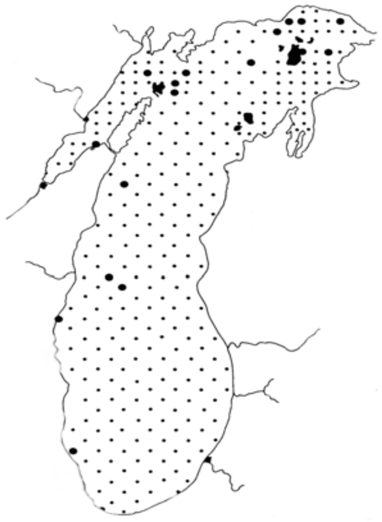
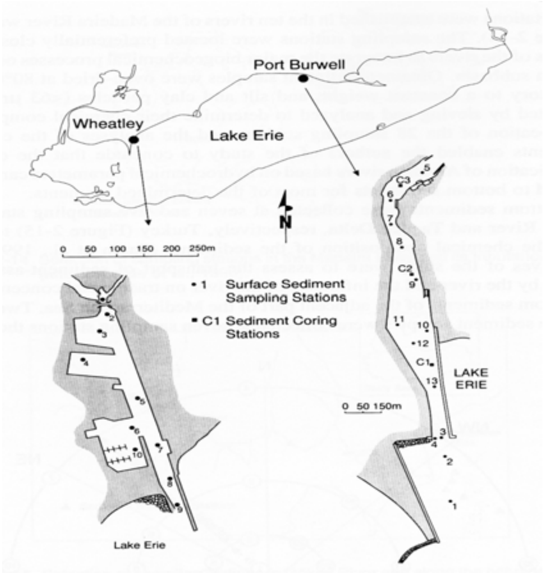
[3] In bioassay nomenclature, reference sediments are distinguished from control sediments. Control sediments are the support matrix for the bioassay test organisms and serve to confirm that the organisms are healthy during testing. Although control sediments can be taken in the field, they are generally prepared in the laboratory in order to control their properties.

those of the dredging site, however, in terms of such things as depths, currents, particle size distribution and the presence of organic debris.



Systematic

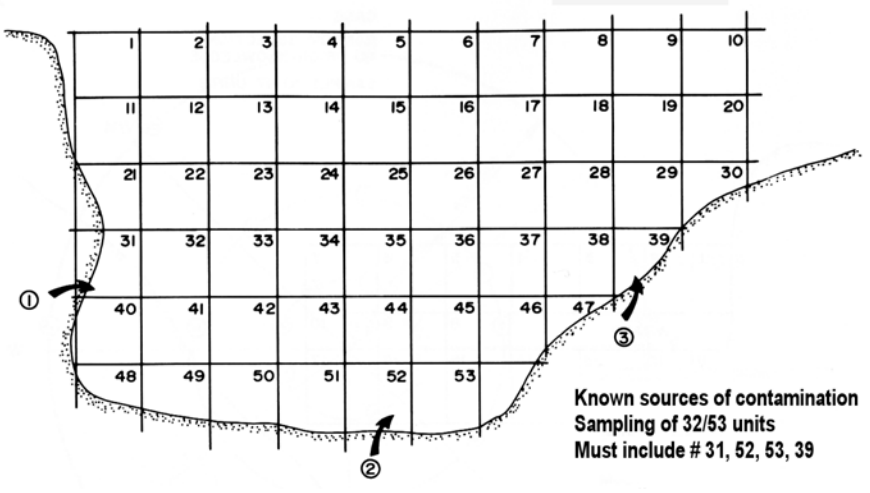
(Cahill, 1981, *Geochemistry of recent Lake Michigan sediments*, with permission)



Deterministic

(Thomas et Mudroch, 1979, *Small Craft Harbours: sediment study: Lakes Ontario, Erie and St.Clair: Dredging summary protocol*)

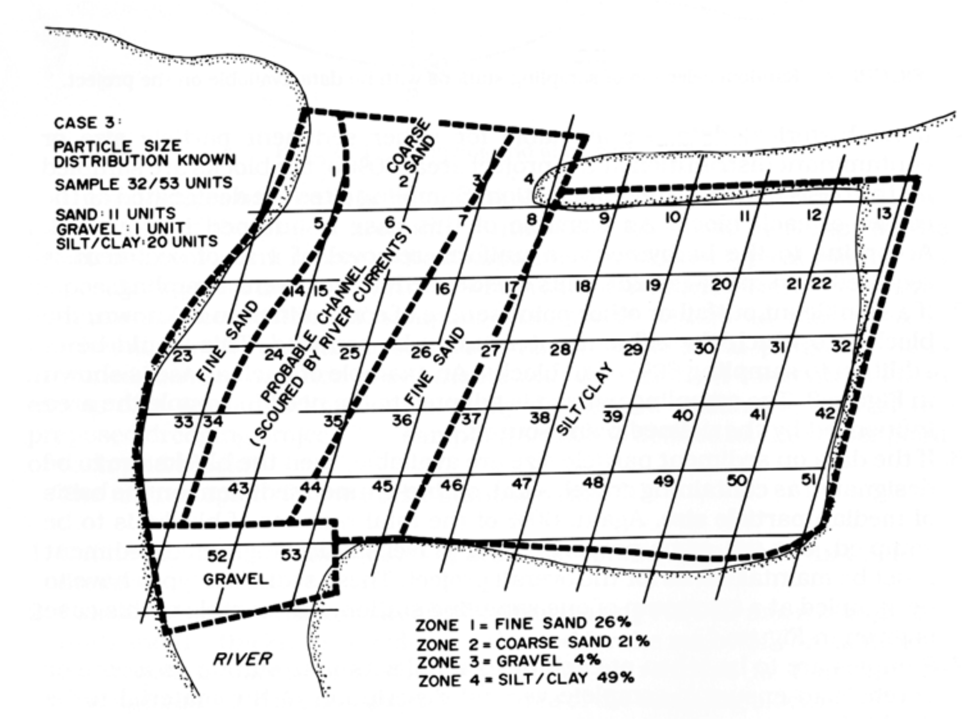
Figure 3.2 Examples of sampling plans



Known sources of contamination
Sampling of 32/53 units
Must include # 31, 52, 53, 39

Random

(Mudroch et MacKnight, 1994*, Handbook of techniques for aquatic sediments sampling*, p.26, with permission)



CASE 3:
PARTICLE SIZE DISTRIBUTION KNOWN
SAMPLE 32/53 UNITS

SAND: 11 UNITS
GRAVEL: 1 UNIT
SILT/CLAY: 20 UNITS

ZONE 1 = FINE SAND 26%
ZONE 2 = COARSE SAND 21%
ZONE 3 = GRAVEL 4%
ZONE 4 = SILT/CLAY 49%

Stratified random

(Mudroch et MacKnight, 1994, *Handbook of techniques for aquatic sediments sampling*, p.26, with permission)

Figure 3.2 **Examples of sampling plans (cont'd.)**

3.3.2.3 Sampling effort

a) ***Sample replicates***

When carrying out sampling at a station, a supplementary or reserve sample can be useful for quality control purposes. Such replicates can be of two types:

- a field replicate, obtained from a reserve or supplementary sample and which results from the independent sampling of the same station
- a split sample (pseudo-replicate), obtained by dividing the same sample into at least two distinct parts (subsamples).

In the first case, the results will show variations due to the techniques used for sampling and the division of the samples, as well as the heterogeneity of sediments within the sampling station.

Split samples are used to determine the variance resulting from handling for homogenisation and analysis purposes. This type of replicate cannot be used to determine intra-site variability in sediment properties.

To determine the level of homogeneity (or heterogeneity) of sediment properties within a given station or strata (intra-site and inter-site variability), the results from replicates, in other words, samples that underwent all the same stages of sampling and subsampling at a given station, must be compared. By determining the intra-site and inter-site variability, the user can define an interval of concentration variation for each stratum and for the entire study area. Replicate samples must be taken from at least one station per stratum. At least three replicates and preferably five must be taken and each must be separately homogenized. The sampling vessel must be moved a small distance between each replicate to avoid sampling sediments disturbed by the previous sampling operation.

b) ***Number of samples and sampling stations***

The number of samples to be taken and the selected number of sampling stations are usually determined by (1) the size of the study area (dredging area, zone of influence and open-water disposal site); (2) objectives of the sediment characterization study (physicochemical and toxicity assessment); (3) nature, distribution and concentration of contaminants under evaluation; (4) characteristics and homogeneity of sediments; (5)

analytical constraints (volume of materials required) and (6) desired confidence level required to determine the mean result.

Several different approaches can be used to determine the number of samples required. Regardless of the approach selected, some basic principles must be followed:

- the greater the number of samples, the better the characterization of the spatial distribution pattern
- single measurements are inadequate to describe variability
- determining the mean of several measurements at each station (replicates) is less variable than a single measurement.

The number of samples to be analysed can be determined empirically or statistically. When statistics are used, historical data or data from exploratory sampling must be available.

Empirical approach. In this guide, only one empirical approach is proposed for determining the number of sampling stations.

This approach involves subdividing the dredging area into square or triangular sections or blocks of equal size. The number of blocks to be sampled is defined according to the dredging volume.

- Each stratum identified based on historical information must be divided using a numbered grid.
- The number of blocks to be sampled is based on the dredging volume (in m^3) (Table B.1, Appendix B). Sampling stations must be located in the centre of the blocks. Blocks on the boundary of the dredging area will be included in the sampling plan if their centres are located within the dredging area.
- For projects with a dredging volume of less than 50 000 m^3, the size of the sampling blocks must not be greater than 625 m^2 (25 m x 25 m). For larger projects, the number of blocks must be equal to at least five times the number of samples recommended in Table B.1 (Appendix B), with their size to be calculated accordingly.
- When the excavation depth varies, the area to be sampled must be divided into two or more areas. The samples will be divided among the different areas by taking account of the volume of each in relation to the total volume of sediments to be dredged.

- Random numbers, taken from a table or generated electronically (calculator, spreadsheet), will serve to identify the blocks to be sampled.
- Although representative samples may be obtained by random sampling, a systematic sampling approach is often preferable.
- The number of stations must be greater in highly industrialized areas and those where effluent is present. A station must be located in the block where the effluent is located.
- In each area, sampling stations must be distributed proportionally among the various strata according to excavation depth and sediment type. A much greater emphasis must be put on the fine fraction than on the gravel fraction since the former generally contains the highest contaminant concentrations.
- In gravelly areas, only two samples need to be taken if it can be demonstrated that no contaminated fine matrix is present.

Statistical approach. One of the most important applications of statistics is in determining the minimum sample size while maintaining uncertainty at an acceptable level. Preliminary or exploratory data indicating that contaminant concentrations are near decision-making criteria pose a problem since the information obtained in sampling is somewhat random. These statistical methods are described mainly for informational purposes since, in practice, this type of approach requires a large number of stations for even small projects.

First, it must be determined what types of comparisons will be made with the data generated and at what confidence level the differences will be tested. Using such an approach requires knowledge of the variability of data in the study area, based on either historical data or exploratory sampling. The confidence limits (usually between 80% and 99%) and maximum deviation with respect to a standard (5–40%) must be determined. Inputs consist of mean concentrations, the standard deviation for the different parameters analysed and the comparison threshold (criterion).

Appendix A gives some of the basic equations for performing these calculations. The traditional approach is based solely on the notion of probability; the results can occasionally lead to fairly large sample sizes. In some cases, it is obvious that the sample size is disproportionately large given such things as the sampling cost, the economic costs of environmental impacts and the cost of decontamination.

To deal with these problems, Bayesian statistics can be used. In determining the optimum sample size, Bayesian statistics takes into account not only the probabilities associated with uncertainty but also the total cost. This approach also requires an assessment of the social costs related to the presence of contamination. Although the notion of economic cost is used relatively infrequently in environmental sampling, the literature on the subject is abundant. Both the United States Environmental Protection Agency (USEPA) and Environment Canada have carried out a number of economic studies on various environmental problems, most of which are available on the Internet.

Appendix C describes the potential of Bayesian analysis as a decision-support tool and, through examples, shows the difference between the traditional and Bayesian approaches.

c) Types of samples

Depending on the study design objectives, two types of samples can be collected at a given station:

- spot sample
- composite sample.

A *spot sample* comes from a single sampling station but may be obtained with one or more passes of the sampler. In the latter case, the boat may be moved a small distance to ensure that successive passes do not collect material reworked by previous passes. A *composite sample* differs from the above in that it is composed of sediments from different sites in equal proportions. The sediments are then homogenized to incorporate intrasite variability. The sediments can come from a single station of a given area, or from different stations that are to be integrated into a single stratum of the sampling plan. In the latter case, the boat must be moved from station to station and the positions of the points where sediments are collected must be recorded

3.3.2.4. Determining location of sampling stations

The accurate positioning of sampling stations is crucial in sediment characterization studies since contaminated sediments may be distributed in narrow strips along channels and docks or in the form of pockets. In addition, the use of spatial interpolation and representation techniques for determining sediment characteristics during the data processing stage requires precise locations in order to minimize mapping inaccuracies.

Before samples are taken, an effort must be made to ensure that the vessel is positioned at the previously identified location Two anchors should be used to ensure the vessel does not move when collecting multiple samples at a station and to maximize sampler performance.

A differential global positioning system (DGPS), which uses a correction factor provided by the Canadian Coast Guard's network of beacons, seems to be the most suitable for dredging projects. Since May 2000, when satellite signals were unscrambled, the positioning accuracy of standard GPS's (without differential correction) has been greatly improved. Accuracy must be validated regardless of whether DGPS or GPS is used.[4] At the data processing stage, one must ensure that the datum used during the sampling campaign corresponds to the datum used for cartographic data representation.

3.3.2.5 Choice of sampling equipment

The selection of a sampling device must be based on a number of factors including the hoisting equipment required, physical constraints of the environment (currents, bathymetry, waves), the penetration depth required, sample integrity, type of material used to make the sampler (to avoid sample contamination) and the sample volume required for analysis purposes. The recovery of small sample quantities indicates equipment malfunction or improper selection. The characteristics of an ideal sampler are shown in Table 5.1 of volume II (*Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River: Field Operations Manual)*.

For sampling pore water, the sample volume and time constraints, which are determined based on the study objectives, will guide the choice of sampling method. The four main methods are described in Section 5.2.2 of volume II (*Sediment Sampling Guide for*

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[4] For example, by comparing the reading from the instrument with the known position of a geodetic marker.

Dredging and Marine Engineering Projects in the St. Lawrence River: Field Operations Manual).

a) Sediments

Grab samplers. Grab samplers are equipped with a set of jaws operated by a mechanism that closes the jaws when they come into contact with the sediment. The advantage of grab samplers over other types is that they can collect a greater volume of sediments and are easier to use. On the other hand, their disadvantages include the fact that that they do not have a consistent penetration level and they remix the sediments, particularly when overpenetration occurs. Grab samplers are therefore recommended for recurrent dredging projects and when sediments are homogeneous or continually remixed by passing ships. Grab samplers should be selected based on the following criteria:

- nature of the sediments to be sampled
- volume of samples
- strength of currents
- logistical support required (vessel, work space, adequate winches and lifting boom).

Corers. Corers are basically tubes that are sunk into sediments by various means to obtain a core of known length, which is then used to characterize the properties of the sediments according to the depth. In the case of dredging projects, it is generally recommended that the entire thickness of the sediments to be excavated should be characterized. In some cases, the underlying sediments that will be exposed should be characterized as well. Corers allow for the characterization of the entire sediment column and generally allow unmixed samples to be obtained.[5] These samplers are particularly. recommended for collecting samples from which the pore water is to be extracted.

Corers can be divided into four main categories:

- Hand/mechanical core

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[5] The main characteristics affecting sampling performance and quality are the core diameter and penetration speed. Typically, large-diameter corers operating at a slow speed provide better quality samples.

- Gravity corers (including piston corers), which penetrate the sediments using attached weights
- Vibro-corers, which penetrate the sediments by gravity, assisted by the use of a vibrating head that liquefies the sedimentary material around the corer.

Disadvantages of corers include insufficient penetration, core distortion and sample loss during corer retrieval. Large-diameter corers (> 10 cm) are particularly suited to the collection of samples of sufficient quality and volume to meet analytical requirements; on the other hand, they tend to let sediment escape because of the lack of a core catcher. Using a core catcher, however, may result in the remixing of sediments during penetration. Using divers to close the corer may solve this problem. In the selection of a corer, the nature of the sediments, stratigraphy and presence of debris potentially affecting penetration and sample quality must be taken into account.

In general, the subsampling interval must be of reasonable thickness, to be dictated by the dredging techniques to be used. In other words, there is no point subsampling a sediment core at intervals of one centimetre when the dredging accuracy is less than 0.5 m or even 1 m.

b) Pore water

There are four main methods for extracting pore water:

- *In situ* methods:
  - dialysis
  - direct suction.
- Indirect methods (in the laboratory):
  - centrifugation
  - squeezing.

In situ methods are generally recommended because they help prevent changes to the sample caused by temperature, pressure and oxygen. Their main disadvantage is the small volume of pore water produced, mainly because of the long length of time required for equilibration in dialysis and suction in the direct suction method. In addition, equilibrium may not be obtained because of the limits of diffusion in sediments and the ability of membranes to absorb dissolved elements (Grigg et al. 1999, Environment Canada 1994).

In situ methods, therefore, are best suited to small volumes (less than 0.5–1 L).

Indirect methods, which involve the extraction of pore water from sediments previously collected, cause more disturbance to the sample. The main artefacts of these methods include the exposure of pore water to oxidation and increased temperatures and chemical selection by filters. Such methods are preferable, however, for obtaining the large volumes (1–3 L) required for toxicity assays.

3.3.2.6 Handling, preserving and storing samples

Samples may be handled aboard the boat or in the laboratory (field or analytic laboratory). The advantages of handling samples in the field include:

- The ability to easily replace a sample that has been lost for various reasons
- The ability to determine immediately whether sufficient quantities of sediment have been collected
- The option of carrying out a visual or olfactory evaluation of samples in the field in order to improve the original sampling plan without affecting operations
- The ability to return excess samples to the aquatic environment.

The prerequisites for handling samples depend on the project and must be described in the quality assurance and control program. The following aspects must be taken into account:

- Volume to be collected
- Number and type of samples (replicates and split samples)
- The types of analyses to be carried out and constraints on sample containers and preservation (temperature, duration).
- Documentation of samples, including:
  - date of collection
  - time of collection
  - name of project and sample identification number
  - name of collector
  - sampling site

- sampling interval
- sampling conditions or type of sample
- sampling equipment
- preservation method
- shelf life of sample
- observations on sampling site (additional descriptive data).

The field staff must be familiar with sample handling techniques to avoid contamination and ensure sample representativeness and integrity. Sample exposure to contamination sources must be minimized. Strict quality control rules must be enforced in the field to reduce or eliminate contamination risks (engines turned off, no smoking, etc.).

In addition, at some sites, contaminant levels increase along with proximity to sources of atmospheric emissions or effluent discharges. Consequently, sampling stations should be visited in a sequence that limits potential cross contamination by ensuring samples are collected at the least contaminated stations first. This does not eliminate the need to clean and condition the sampler before each sample, however.

Generally the analytical laboratory will also provide sample bottles, preservative and clear instructions on taking samples. The containers provided by the laboratory must meet the quality objectives set for the study.

Chapter 8 of volume II (*Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River: Field Operations Manual)* provides in-depth information on preserving sediment and pore water samples.

3.3.2.7 Logistics

The success of a sampling campaign depends on judicious planning, which should include logistical aspects such as site access, field operations, the formulation of contingency plans and time lines. A preliminary site visit is usually recommended to familiarize oneself with the layout of the site and sampling conditions, make observations to facilitate the formulation of the sampling plan, and make contact with local authorities, among other things.

Of course, unforeseen circumstances are to be expected during most sampling activities. Contingency plans and alternatives should therefore be prepared. The longer and more complex the project, the greater the chance of potential pitfalls. Therefore, provisions should be made for back-up samplers (in the event of loss or malfunction), additional containers, and the like. Sampling delays may result in delayed shipments to the laboratory. Previous arrangements must be made with the laboratory so that the samples received are preserved adequately and analysis deadlines are met.

Safety risks to field personnel involve several areas, due to the nature of the work: risks associated with working on the water, the operation of samplers and hoisting devices, the use of reagents (solvents, acids) and exposure to contaminants. Individuals on the field team should be accustomed to working on and operating boats on various bodies of water and using different sampling and hoisting devices according to their operating limits.

Field campaign planning should also include the preparation of a list of emergency telephone numbers (police, Coast Guard, search and rescue, hospital emergency). This list should be made available aboard the vessel, along with the minimum safety equipment required under the standards applicable to the project. In addition, some clients (industries, government agencies) may have their own safety standards for fieldwork that also apply to the consultants they hire.

Weather conditions and constraints should be taken into account in planning the schedule for the sampling campaign and provision should be made for a realistic level of effort so that the field staff has enough time to do the work properly.

3.4 VERIFICATION OF STUDY DESIGN

The formulation of a study design is a multi-stage and multifaceted process, allowing a precise approach to be devised for generating high quality data that can be interpreted without ambiguity. The success of a characterization study depends on the effort and means employed to implement and enforce the different aspects of the quality assurance and control program. Some of the main areas that must be carefully considered include resources, timetable, operating time, centres of responsibility, performance indicators, phases, risk factors, impacts and unexpected problems. A list of questions to help formulate and revise a study design is provided in Table 3.3. Some of the questions involve terms dealing with quality control, which are discussed in Section 4.

Table 3.3
Verifying the sampling plan

What are your data quality objectives (DQOs)?
- What will you do if your DQOs are not met (sample a second time or revise DQOs)?

Have data quality indicators (DQIs) been defined and are they realistic?
- Have acceptance criteria for samples been defined?

According to program objectives, is exploratory sampling, or exhaustive sampling, or both, required?

Has sampling at the sites been organized?
- Have back-up plans been formulated in the event that all sites cannot be sampled?

Is specialized sampling equipment needed and/or available?
- Is a specific hoisting system and/or vessel needed and/or available?

Do collectors have experience in the type of sampling required?
- Are collectors familiar with the field conditions?

Is a list available of all the substances to be analysed?
- Is the detection limit for each established?
- Have methods been specified for each substance?
- What size of sample is required given the method and detection limit?

Give a list of specific QA/QC protocols required (sound laboratory practices, federal, provincial or specific to method).
- Do they involve percentages or numbers and types required of QC samples?
- Is special equipment calibration needed or are there any other special requirements?

What approach will be used for sampling?
- Random, deterministic or a combination of the two?
- Will the sampling allow DQOs to be met?

What data analysis methods will be used?
- Geostatistics, control charts, hypothesis tests, etc.
- Do the data analysis methods satisfy the DQOs?
- Is the sampling approach compatible with the data analysis methods?

How many samples are required?
- How many sampling sites are there?
- How many methods are required?
- How many samples are needed for each method?
- How many samples are needed from the reference site?
- What types of QC samples are needed?
- Will the QC samples satisfy the DQOs?
- How many of each type of QC sample are needed?
- How many exploratory samples are needed?
- How many supplementary samples will be taken?

Number of samples = Test + Control + QC + Exploratory + Supplementary
- Test samples = Methods x Sites to be sampled x Samples per site
- Control samples = Methods x Sites to be sampled x Samples per site
- QC samples = Methods x Type of QC sample x % necessary to satisfy DQOs
- Exploratory samples = (test samples + control samples) x 5–15%
- Supplementary samples = (test samples + control samples) x 5–15%

4 Quality Assurance and Control Program

4.1 OVERVIEW

The success of a characterization study depends on the quality of sampling. Therefore, it is essential to ensure samples are properly collected. The study design must include a quality assurance and control (QA/QC) program for sampling operations and the preservation of sediments for analysis purposes. Such a program is developed in four main steps:

- Formulation of quality objectives
- Choice of quality indicators
- Development of standard operating procedures
- Drafting of a quality assurance and control program.

The quality assurance and control program should also include contingency plans with detailed description of alternatives. The typical contents of a QA/QC program are shown in Table 4.3 (Section 4.5)

4.2 DATA QUALITY OBJECTIVES

Data quality objectives (DQOs), an essential part of the QA/QC program, target all aspects of a sediment characterization operation, from the collection and analysis of the samples to data processing and presentation. Establishing data quality objectives allows the confidence level required to draw conclusions from all the data collected in the project to be defined. These objectives therefore determine, for the data collected, the degree of total variability and acceptable error rate to be taken into account in the sampling and analysis plan.

Data quality objectives are defined using an iterative process that facilitates the sequential examination of a series of relevant questions (Table 4.1).

Table 4.1
Steps in the formulation of data quality objectives

Step 1	State the problem to be solved	What problems will be studied and what are the objectives of the project?
Step 2	Determine the decision to be made	What specific decisions must be made or questions resolved, on the basis of the data to be collected?
Step 3	Determine the type of data needed to make a decision	What types of data are required (e.g. physical, chemical, biological), how are the data to be obtained and managed and how will they be used in decision-making?
Step 4	Define the limits of the study area	What are the spatial limits of the study area and what are the temporal limits?
Step 5	Determine the decision-making process	How are the data collected to be synthesized and interpreted in order to make a decision?
Step 6	Identify constraints on performance	What are acceptable performance limits and constraints that will reduce performance?
Step 7	Optimize study design to obtain the best data possible given the budget available	What is the optimal (and most rational) approach in terms of the cost-benefit ratio for meeting data quality objectives?

(Modified from CCME, 1993 and USEPA,1994)

The process of formulating DQOs involves seven steps.

- Specify the nature of the problem and identify time limits and amount of resources required for the sample collection phase based on site constraints. The prior knowledge required (historical information) and available resources must also be determined.
- Identify activities that will allow the information to be synthesized and decisions made.
- Identify the factors to be taken into account in decision making in order to ensure that the necessary information is obtained (substances to be analysed, characterization of disposal or reference sites, etc).
- Define the boundaries of the study area (or zone of influence of project) to target the sampling effort to the appropriate sites. For most dredging projects, the study area will be limited to the physical boundaries of the port, basins, etc. On the other hand, boundaries of natural areas, particularly disposal areas, are more difficult to identify, particularly since temporal variations may occur in sectors with active sediment transport.
- Establish a decision-making process based on data use. How the data are to be used must be specified, in order to determine the sediment management method. Statements must include results, such that, “If the result is the following, the following must be done.” This step allows a more precise definition of the type of data needed to make informed decisions.

- Determine the acceptable performance limits for the data gathered. In the context of sediment sampling work, this may mean the minimum number of data to be taken into account or the minimum sampler performance (penetration, volume collected, sample integrity, number of samples). In the context of the entire study, this translates into the rate of error (the percentage of false positives or false negatives) that can be accepted. (To get an idea of these types of errors, a sampling strategy using field blanks and duplicates must be formulated). This aspect of defining quality objectives touches on an important point in the study design, sample representativeness, which depends on the sampling effort and quality. The most common sources of error are shown in Table 4.2.
- Review the preceding steps to define an optimal study design in terms of data quality and the time and resources available to attain the objectives.

Although this process may seem complex, it is often carried out more or less intuitively when planning a sampling campaign but is usually not documented. An adequate amount of time must be allotted to the process so that it may be properly documented.

4.3 DATA QUALITY INDICATORS

Whether quantitative or qualitative in nature, data quality indicators (DQIs) are used to define the usefulness of the data generated. DQIs, which include data sensitivity, precision, accuracy, representativeness and comparability, apply equally to the sampling plan as to field measurements and laboratory analyses. Qualitative DQIs concern mainly chemical analyses. In the field, they apply to measurements of the environmental conditions of sampling (pH, Eh, temperature, positioning, depth) made with calibratable devices as well as certain sample collection parameters (volume collected, sampler penetration, ascent and descent speed, etc.). Data quality indicators also include the collection of replicates to evaluate the precision of the sampling technique.

Parameters describing sample representativeness, the justifications on which the sampling plan is based (choice of approach, subdivisions, number of stations) and sample handling procedures are the most important DQIs.

Table 4.2
Common sources of error

Sources of overall error (in descending order of importance)

☐ Spatial distribution of contaminants
☐ Inadequate sampling plan and problems with sample collection
☐ Sampling and sample handling procedures
☐ Preparation of samples in the laboratory
☐ Poor choice of analysis method and analysis errors
☐ Undetected disturbance of matrix
☐ Data handling and processing

Sampling and collection plan

☐ Heterogeneous distribution of contaminants
☐ Insufficient number of samples
☐ Non-representative sampling station
☐ Remobilization of contaminated sediments and/or contaminant migration
☐ Improper sampling approach

Sampling and analysis errors

☐ Biased sampling
☐ Station positioning and location errors
☐ Sample mixup before labelling
☐ Labelling error
☐ Inadequate sampler
☐ Cross contamination (between stations due to inadequate cleaning)
☐ Remixing of sample (e.g. properties of pore water)
☐ Inadequate sample preservation
☐ Sample preparation in the laboratory or analysis error
☐ Subsampling error
☐ Lost samples
☐ Contamination of samples or analytical instruments
☐ Incorrect sampling protocol
☐ Incorrect uncertainty limit for various matrices (sediments, pore water)
☐ Incorrect calibration or reference

(Adapted from USEPA, 1994; CCME,1993 and USEPA/USACE, 1998b)

4.4 STANDARD OPERATING PROCEDURES

Standard operating procedures (SOPs) consist of a written description of the activities involved in taking and handling samples and subsamples, transporting, storing and preserving samples and documenting analysis results. The drafting and implementation of these procedures ensures consistency and integrity in the use of the various techniques and reduces the risk of errors due to erroneous extrapolations or suppositions. The use of field notes to record daily activities in the field also ensures that all steps are followed. Issues related to the preparation of sampling protocols are shown in Table C.1 of Appendix C of volume II (*Sediment Sampling Guide for Dredging and Marine Engineering Projects in the St. Lawrence River: Field Operations Manual)*. The sampling protocol must contain:

- The sites where samples will be taken.
- Equipment and information required for standard sampling operations:
  - number and size of containers
  - type of labels to be used
  - logs for fieldwork
  - type of samplers
  - calibration methods and frequency
  - number and type of field blanks
  - sample size and number of spiked samples
  - sample volume
  - number and type of composite samples (incorporating 3 or 5 samples)
  - specific instructions on preservation for each type of sample
  - operations related to chain of custody of samples
  - sample transport plan
  - field preparations (e.g. filtration or pH adjustment)
  - field measurements (e.g. pH, dissolved oxygen level, etc.)
  - presentation of project report.

In addition, the protocol must include the physical, meteorological and hydrological variables to be recorded or measured during sampling. Precise details on analytical techniques already standardized for accredited laboratories do not need to be included, however. On the other hand, the choice of analytical techniques must be taken into account insofar as the attainment of detection limits depends mainly on the volume and characteristics of the sample provided to the laboratory. The person in charge of planning the sampling campaign should provide the laboratory representative with information on the nature of sediments (historical data, and data obtained from the preliminary site investigation and exploratory sampling) in order to allow minimum sample requirements to be determined. In addition, providing information on field conditions and sediment characteristics may also allow analysis methods to be adapted to specific conditions in the study area.

4.5 IMPLEMENTING THE QUALITY ASSURANCE AND CONTROL PROGRAM

4.5.1 Role

The quality assurance and control program is a crucial element of the planning process since it contains all the technical (SOPs) and quality (DQOs and DQIs) aspects of a given project. This document, in which the project team undertakes to implement quality assurance and control policies, describes the policies, organization, objectives and operational responsibilities put in place to ensure quality objectives are achieved. The five main roles of a QA/QC program are to:

- state the goal of the QA/QC program
- describe the process used to implement the QA/QC program
- describe the resources allocated to carrying out quality assurance and control work
- determine which projects require quality assurance and control project plans
- describe how the implementation of quality assurance and control will be evaluated.

4.5.2 Content

The QA/QC program is used during the planning stage to ensure that all aspects of the study have been taken into account. During the actual project, it serves as a reference document for the entire project team (field, laboratory, data processing and interpretation). The QA/QC program helps ensure the quality of data generated by:

- providing standardized information to all participating organizations
- describing field operations in detail
- taking account of the selection criteria for sampling sites in the sampling plan
- specifying quality assurance and control objectives for data comparability, precision, representativeness and integrity
- providing information on equipment calibration and maintenance
- providing information on safety practices to be used in sampling and testing operations in the field
- providing accepted methods for defining errors due to field measurements
- defining statistical techniques for evaluating experimental data
- ensuring that the data gathered meet measurement program objectives.

The typical contents of a QA/QC program are shown in Table 4.3.

4.5.3 Importance of providing integrated project information

The field staff must accurately describe sampling conditions in order to determine whether DQOs have been met. The person in charge of documenting activities and describing samples must note any deviations from the sampling protocol.

Consequently, personnel in charge of processing and managing the data must verify the data, ensure they are valid and evaluate their consistency, integrity and reliability. An overall understanding of the problems posed by a contaminated site can only be obtained after the data have been evaluated. In the report, the data must be presented along with a description of any problems encountered so that a link may be made with the results.

Table 4.3
Table of contents for a quality assurance and control program
(including aspects related to laboratory work)

- **1 Description of project**
  - 1.1 Introduction
  - 1.2 Project framework
  - 1.3 Data quality objectives
  - 1.4 Basis for and organization of sampling plan
  - 1.5 Implementation of project
- **2 Project organization and responsibility**
  - 2.1 Organization
  - 2.2 Authority and responsibility
  - 2.2.1 Project supervision
  - 2.2.2 Fieldwork
  - 2.2.3 Laboratory analyses
  - 2.2.4 Other personnel
  - 2.3 Communications
- **2 Data quality objectives**
  - 3.1 Quality assurance objectives for project
  - 3.2 Field measurement quality objectives
  - 3.2.1 Positioning
  - 3.2.2 Sampling parameters
  - 3.3 Laboratory data quality objectives
- **4 Sampling and handling procedures**
  - 4.1 Sample containers
  - 4.1.1 Volume and type
  - 4.1.2 Quality control and storage
  - 4.2 Sampling procedures
  - 4.2.1 Equipment selection and decontamination
  - 4.2.2 Sampling methods
  - 4.2.3 Sampling
  - 4.2.4 Volume and preservation of samples and duration of sample collection
  - 4.2.5 Waste generated in the field
  - 4.3 Packaging and transportation of samples
- **5 Sample documentation and preservation**
  - 5.1 Field procedures
  - 5.1.1 Labelling of samples
  - 5.1.2 Field notebooks
  - 5.1.3 Chain of responsibility in the field
  - 5.1.4 Transfer of responsibility
  - 5.2 Laboratory procedures
  - 5.2.1 Sample inventory and control
  - 5.2.2 Receiving and handling samples
  - 5.2.3 Field notebooks and chain of responsibility
  - 5.2.4 Disposal of samples
  - 5.3 Final data
  - 5.3.1 Contents
  - 5.3.2 Responsibility procedure
- **6 Calibration procedures and frequency**
  - 6.1 Field measurements
  - 6.1.1 Recording and monitoring of calibration check samples
  - 6.1.2 Initial and ongoing calibration procedures
  - 6.1.3 Calibration threshold values
  - 6.2 Physical and chemical analyses of sediments in the laboratory
  - 6.2.1 Recording and follow-up of calibration samples
  - 6.2.2 Preparation and storage of calibration check samples
  - 6.2.3 Initial and ongoing calibration procedures
  - 6.2.4 Calibration threshold values
  - 6.3 Biological-effects tests
  - 6.3.1 Recording and follow-up of calibration check samples
  - 6.3.2 Initial and ongoing calibration procedures
  - 6.3.3 Calibration threshold values

Table 4.3 (cont'd.)
Table of contents for a quality assurance and control program (including aspects related to laboratory work)

7 Standard operating procedures

7.1 Field measurements
7.1.1 Positioning
7.1.2 Sampling parameters
7.1.2.1 Sediments
7.1.2.2 Pore water

7.2 Chemical analysis of sediments
7.2.1 Sediment preparation methods
7.2.2 Sample cleaning and extraction methods
7.2.3 Analytical methods

7.3 Analyses of other sediments

7.4 Biological-effects tests

8 Internal quality control indicators

8.1 Sampling

8.2 Field measurements

8.3 Chemical analyses of sediments

8.4 Analyses of other sediments

8.5 Biological-effects tests

9 Data sorting, validation and reporting

9.1 Field measurements

9.2 Laboratory data
9.2.1 Sorting of internal data
9.2.2 Data reporting requirements
9.2.3 Validation of external data

10 Performance and system audits

10.1 Schedule and planning of audits

10.2 Internal audits
10.2.1 Field activities
10.2.2 Laboratory activities
10.2.2.1 System
10.2.2.2 Performance

10.3 External audits
10.3.1 Field activities
10.3.2 Laboratory activities
10.3.2.1 System
10.3.2.2 Performance

10.4 Audit reporting

11 Preventive maintenance

11.1 Field equipment

11.2 Sampling equipment

11.3 Laboratory instruments

11.4 Computer software and parts

12 Specific data-use evaluation procedures

12.1 Sampling

12.2 Field and laboratory data
12.2.1 Data quality indicators
12.2.1.1 Sensitivity
12.2.1.2 Precision
12.2.1.3 Accuracy
12.2.1.4 Completeness
12.2.2 Review of other data

13 Contingencies and alternatives

13.1 Introduction

13.2 Equipment breakage

13.3 Procedural problems

13.4 Break in chain of responsibility of samples

13.5 Lack of documentation

13.6 Data anomalies

13.7 Hindrances in performance audits

13.8 Hindrances in system audits

14 Quality assurance reports to management

14.1 Project-specific final reports

14.2 Contingencies and alternatives memos

14.3 Internal and external audit reports

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(Modified from USEPA, 1992)

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APPENDIX A Statistical Formulas for Calculating Sample Size

(Serge Morissette, Centre d'Expertise en Analyse Environnementale du Québec, February 2001)

The appendix gives the usual equations for calculating sample size when the measured levels of contamination are close to the standard. These equations, which only apply when contaminant distribution is random, can be used to determine the sample size required to improve the precision of an experiment by reducing uncertainty to a predetermined level. Appendix C provides a graphic illustration of the concepts discussed in this section. The only difference is that, in Appendix C, the error risk is asymmetrical. The first equation uses the normal law and is applicable under the conditions shown in Table 1.

$$n = \left[\frac{z_{\alpha/2} \bullet \ s}{\overline{X} - X} \right]^2$$

The level of error or tolerance level[6] that we are willing to accept is represented by $\overline{X} - X$, where $\overline{X}$ is the sample mean and *X,* the actual mean in the population.[7] It is also the value to be tested. *n* designates the desired sample size and *S,* the standard deviation. $z_{\alpha/2}$ is a complementary probability representing the risk of error. This risk consists in obtaining a result outside the tolerance level, when in actual fact, the true result falls within the tolerance level. $\alpha/2$ indicates that the probability is bilateral and symmetrical. For example, if $\alpha = 5\%$, we expect an error risk of 2.5% that the tolerance level will be "accidentally" exceeded and a risk of 2.5% that the value will be below this level. Usually, this test is expressed in the form of a total percentage (e.g. the confidence level for the experiment is 95%).

This type of equation can be useful during the planning stage, for estimating a realistic sample size. Usually managers have little or no information on the mean concentrations that will be obtained. On the other hand, from experience, managers often have a fairly good idea of the standard deviation for a given sampling technique. This

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[6] This parameter represents the range of results that are tolerated. The purpose is to verify if the actual mean is inside or outside the range. The parameter is also similar to the concept of precision. The larger the sample size, the smaller the range at a constant confidence level.

[7] μ is often used to designate the population mean. The difference between μ and $\overline{X}$ therefore represents the error.

equation allows managers to formulate hypotheses and examine the consequences of a sampling method before actually using it.

To simplify the discussion, let us assume that no spatial trend is present, or that correlations have been eliminated by using the appropriate combination of samples. Let us assume that a given sampling technique results in a standard deviation of around 300 mg/kg while the standard is 1000 mg/kg. The mean of the results is not yet known but if it is 900 mg/kg, one would like to be able to state with a confidence level of 95% that the real concentration of the contaminant is less than the standard of 1000 mg/kg. The level of error tolerated is therefore 1000 - 900 = 100 mg/kg.

The value of $z_{\alpha/2} = 0.025$, which is provided in a table of probabilities for the normal law, is 1.96. Consequently, if the standard deviation for the sample is 300 mg/kg, the optimal sample size is:

$$n = \left[\frac{1.96 \bullet 300}{100}\right]^2 = 34.6 \cong 35$$

With a sample size of 35, one can state with a confidence level of 95% that the standard has not been exceeded if the result of the experiment is 900 mg/kg. However, if the actual mean is 900 mg/kg and the experiment is repeated several times, on average, 2.5% of the results will be over 1000 and 2.5% of the results, below 800. The interval [800-1000] very likely contains the actual population mean, but if the experiment is repeated a large number of times, one will find that the mean will be within the interval only 95% of the time. Therefore, there is a risk of making the error of thinking that the concentration is above the standard when, in actual fact, it is 900 mg/kg. This risk can only be reduced by increasing the sample size or increasing the margin of error. In addition, if the standard deviation were lower, the sample size could be reduced; therefore, it is crucial to use methods that reduce random variation.

Although this equation is commonly used, it is problematic since there is really no benefit in imposing conditions for concentrations lower than 800 mg/kg. In general, the only constraint in environmental science is on contaminant concentrations above a given standard. Appendix C describes a case with asymmetrical probabilities; as we will see, this problem can only be solved by using Bayesian statistics.

The second equation uses the Student table and can be used for sample sizes under 30. Table 1 gives more details on the prerequisites for its use. The equation is:

$$n = \left[\frac{t_{\alpha/2,\, n-1} \cdot s}{\overline{X} - X} \right]^2$$

The symbol t signifies that the Student table must be used. The expressions α /2 and $\overline{X} - X$ have the same meaning as in the previous example. The term n-1 is required to identify the value in the Student table. A tentative value must be assumed for the sample size and the calculations repeated. Let us return to the previous example. We will assume that, this time, we expect the mean result to be around 700 mg/kg. If the other values are the same, the difference that we are prepared to accept is 1000 - 700 = 300 mg/kg. To find the Student value for $\alpha/2$ = 0.025, we have to estimate the required sample size (n). Supposing that the sample size is 10, then $t_{0.025,\,9}$ = 2.262 and consequently:

$$n = \left[\frac{2.262 \bullet 300}{300} \right]^2 = 5.11$$

Since we now know that the result will be around 6, we will recalculate the equation using $t_{0.025,\,5}$ = 2.571. The result is now 6.61; if the process is repeated with $t_{0.025,\,6}$, the resulting sample size is 5.98. Consequently, a sample of 6 or 7 appears to be adequate, but 7 is preferable since the greater the sample size, the greater the precision.

Another formula based on the coefficient of variation can be useful for environmental applications since variance depends mainly on the level of contamination (heteroscedasticity). Typically, variance increases with the level of contamination. In the formulation of a hypothesis, the choice of a variance is closely linked to the expected level of contamination. If the actual level of contamination is much lower than expected, the expected variance may be too great and the estimated sample size will be much too large. To deal with this distortion, the coefficient of variation (the standard deviation divided by the mean) can be used. This coefficient remains fairly stable regardless of the contamination level. For more information on this issue, see Gilbert (1987), who also provides a table of the sample sizes required for different confidence levels and standard errors.

The equation can be used with a normal distribution or Student distribution table depending on the elements present (see Table A.1). The equation is:

$$n = \left[\frac{t_{\alpha/2, n-1} \bullet V}{d_r} \right]^2$$

where V represents the coefficient of variation expressed in the form of a ratio rather than a percentage and d_r is the difference that we are willing to tolerate. This difference is expressed in the form of a relative error:

$$d_r = \frac{X - \overline{X}}{\overline{X}}$$

The following table shows in detail the conditions required to use a normal or Student table. It was taken from Martel and Nadeau (1988).

Table A.1
Conditions for using normal and Student tables

Expected distribution	Sample size	σ (S) known	σ (S) unknown
Normal	n ≥ 30	Normal table	Normal table
	n < 30	Normal table	Student table
Abnormal	n ≥ 30	Normal table	Normal table

Note: When the manager can predict the standard deviation fairly accurately from experience, it can be assumed that σ is known.

APPENDIX B Number of Sediment Samples Required for Dredging Projects

Table B.1
Number of sediment samples to be taken* for dredging projects of different sizes

Dredging volume (m^3)		Number of samples
Greater than	But less than	
0	10 000	6
10 000	17 000	7
17 000	23 000	8
23 000	30 000	9
30 000	37 000	10
37 000	43 000	11
43 000	50 000	12
50 000	58 000	13
58 000	67 000	14
67 000	75 000	15
75 000	83 000	16
83 000	92 000	17
92 000	100 000	18
100 000	141 000	19
141 000	182 000	20
182 000	223 000	21
223 000	264 000	22
264 000	305 000	23
305 000	346 000	24
346 000	386 000	25
386 000	427 000	26
427 000	468 000	27
468 000	509 000	28
509 000	519 000	29
519 000	632 000	30
632 000	673 000	31
673 000	714 000	32
714 000	755 000	33
755 000	795 000	34
795 000	836 000	35
836 000	877 000	36
877 000	918 000	37
918 000	959 000	38
959 000	1 000 000	39

For projects with an expected dredging volume of over 1 000 000 m^3, round out the result of the following formula:
40 + (dredging volume – 1 000 000)/75 000 samples

(Atkinson, 1994)

* The number of sampling stations equals the number of samples taken because one sample is taken at each station. If more than one sample is taken at each station, the additional samples must be considered as supplementary ones.

APPENDIX C The Cost of Uncertainty in Environmental Sampling

(Serge Morissette, Centre d'Expertise en Analyse
Environnementale du Québec, September 2000)

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C1 Introduction

This document proposes an alternative approach for evaluating environmental sampling effort when one is not sure whether contaminant concentrations exceed the standards. This method is based on the use of Bayesian[8] mathematics, which allows the notions of probability and cost to be combined in determining the cost effectiveness of obtaining additional information.

Classical statistics use strictly the notion of probability in information processing and the formulation of results. The calculation of sample size, crucial in establishing whether standards have been exceeded, is based mainly on controlling the probabilities of decision-making errors. This approach is incomplete, however, and may even be problematic when there are economic implications. In some cases, the results of the sample size calculations may result in sampling investments much greater than those actually required when total costs are taken into account. Classical statistics is insensitive to any notion of costs. For example, the sample size will remain the same regardless of the volume of sediments to be treated or the treatment cost.

A Bayesian approach allows decision-makers to deal with the probabilities of making incorrect decisions when decisions are associated with economic issues. Economic considerations are expressed in the form of the sampling, restoration and social costs caused by the presence of contamination.

In this document, we will examine the following problem: in the event of uncertainty, do the costs related to making a poor decision justify the allocation of additional resources to sampling in order to reduce uncertainty? If so, what amount must be invested?

The approach used to solve this problem will be illustrated using examples that allow the classical and Bayesian methods to be compared. Examples will be presented in a

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[8] The word "Bayesian" refers to Thomas Bayes, who developed a theory that allows probabilities to be combined with the notion of cost in the development of decision-making methods. This has led to a new school of statistics called Bayesian statistics.

way that helps readers to intuitively understand the problem, avoiding as much as possible aspects associated with mathematical processing.

A normal distribution is used to simplify the discussion and make the explanations more accessible to readers less familiar with statistics. A Bayesian analysis could very well be developed with a lognormal type of distribution, which in fact is the most common type in the environmental sciences. In addition, the discussion assumes that variation depends solely on the distribution of contamination in the sediments; sources of variation related to homogenization and analysis are not discussed. Lastly, the models developed in this text assume that the user's only objective is to measure mean contaminant concentrations and not to define the spatial distribution of contaminants using tools such as geostatistics.

Readers interested in Bayesian mathematics will find a more in-depth discussion, along with several examples of applications in management and economics, in Martel and Nadeau (1988) and Martel (1973).

C2 Information Processing in Classical Statistics

C2.1 Modelling

In statistics, the determination of frequency distribution and statistical parameters such as the mean and standard deviation are the basic tools used in information processing. Figure C.1 shows the frequency distribution for the results of an analysis of sediment samples for a given pollutant. The mean of the distribution is 800 mg/kg and the standard deviation is 300 mg/kg. The concentration deemed harmful is 1000 mg/kg.

In this situation, there is uncertainty about whether contamination levels exceed the standard of 1000 mg/kg. Even though the mean is 800 mg/kg, there is still a significant probability that, taking into account the precision of the experiment, concentrations will be above the standard.

For the purposes of this discussion, therefore, there are two possibilities in terms of the actual concentration, designated as "states of nature":

- The mean concentration is below the standard (designated here by e_0)
- The mean concentration is above the standard (designated here by e_1).

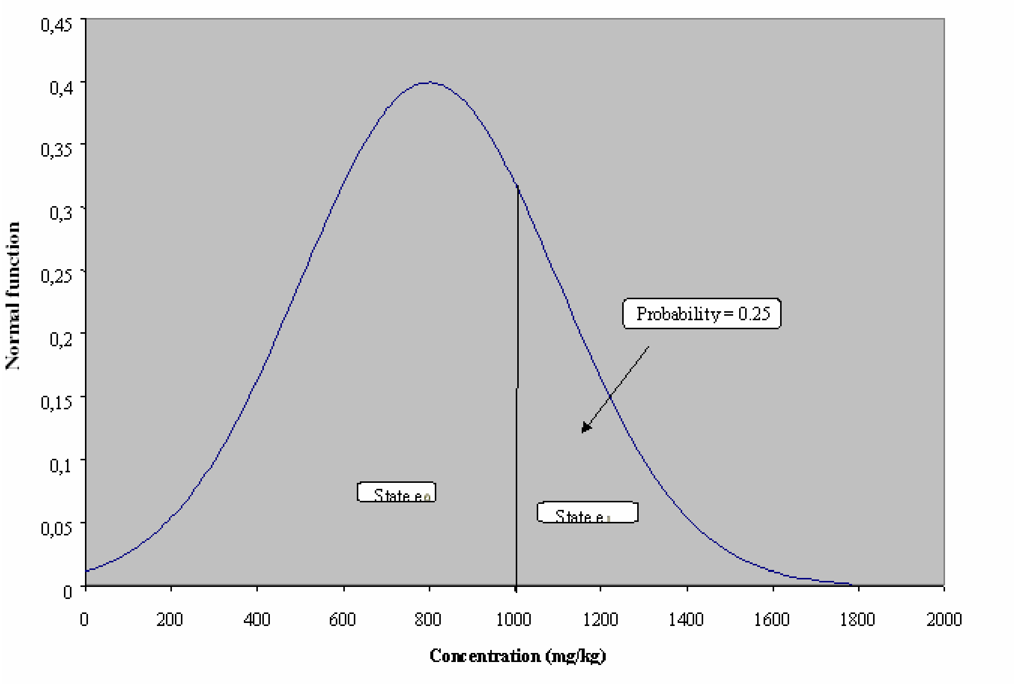

Figure C.1 Distribution of results of sediment analysis

Decision-makers usually have two choices when faced with such a problem. They can conclude that contamination is present at concentrations below the standard and decide to do nothing. Alternately, they can opt for decontamination if they think concentrations are too close to the standard or the risk of exceeding the standard is too great. In short, the alternatives can be defined as follows:

a_0- do nothing
a_1- remove the sediments.

Based on the preliminary information, the normal distribution indicates that there is roughly a 25% chance that the standard of 1000 mg/kg will be exceeded (state e_1) and about a 75% chance that concentrations will be below the standard of 1000 mg/kg (state e_0). Consequently, the decision not to remove the sediments seems, *a priori*, to be the best one, but with a fairly high probability (0.25) that the decision will be an incorrect one. This decision-making problem is summarized below (Table C.1).

Table C.1
Decision matrix for action-state pairs

State of nature	**Action**	
	a_0 (do nothing)	**a_1** (remove)
e_0 (Low contamination P = 0.75)	Correct decision	Incorrect decision
e_1 (High contamination P = 0.25)	Incorrect decision	Correct decision

In classical statistics, uncertainty is reduced by using a sample of sufficient size, based on the notion of probability. This approach, briefly outlined in the following paragraphs, is commonly used in determining whether additional information should be acquired.

C2.2 Decreasing uncertainty

The increased-sample-size approach is based on the fact that, if all the elements of a population are analysed, our knowledge of the phenomenon under study will be complete, reducing the uncertainty to zero or close to zero. The reduction of uncertainty is expressed quantitatively by using the equation $S / \sqrt{n}$. The standard deviation (*S*), which represents the variation around the mean, is reduced by the square root of the sample size (*n*).

Figure C.2 shows a hypothetical sediment surface. It consists of nine sections, with each pattern in the diagram representing a different concentration of pollutants. The distribution of contaminant density is practically perfect since each of the nine areas is of equal size and within each area the contamination level is equal at all points[9].

If samples were taken from a mixture of all nine sections in equal parts, the composition of the samples would be identical. Results that were equal and representative of the mean of the nine sections would always be obtained, regardless of whether the analysis was performed on one or several samples, since each sample is a mixture of the nine sections. The variance would therefore be null.

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[9] It is assumed that the distribution of sections representing different contaminant levels is random. When a correlation is present, techniques like those described in Section 3.2.3.2 must be used.

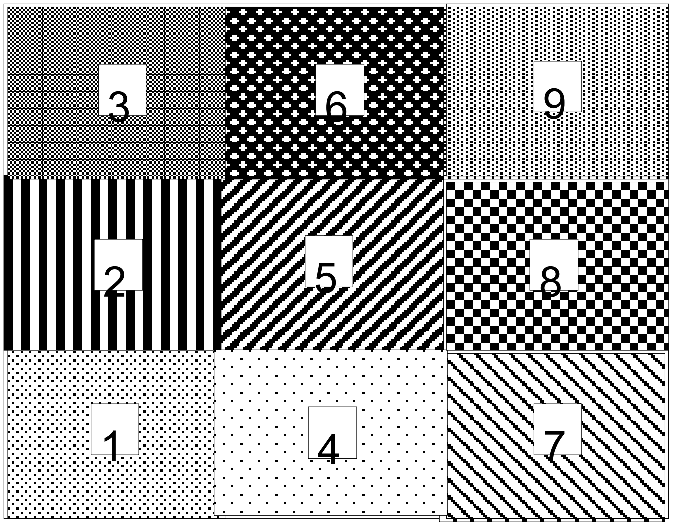

Figure C.2 Hypothetical distribution of pollution density at surface of sediments

In practice, such an arrangement, which furthermore would have to be known in advance, does not exist. According to statistical theory, the standard deviation would be reduced by the factor of $1/\sqrt{n}$ owing to the mixture of subsamples, as long as the other postulates of the statistical laws were met, of course, including a random distribution.

Figure C.3 shows the reduction of the standard deviation for different sample sizes, calculated from the equation $S/\sqrt{n}$ for the example in question.

When the sample size is 10 and the mean concentration is 800 mg/kg, the probability of the concentration being over 1000 mg/kg is no greater than 0.02. Increasing the sample size results in a substantial reduction of uncertainty (from 0.25 to 0.02). In this case, the manager would feel more comfortable in deciding not to act, since the probability of making an incorrect decision would be considerably reduced.

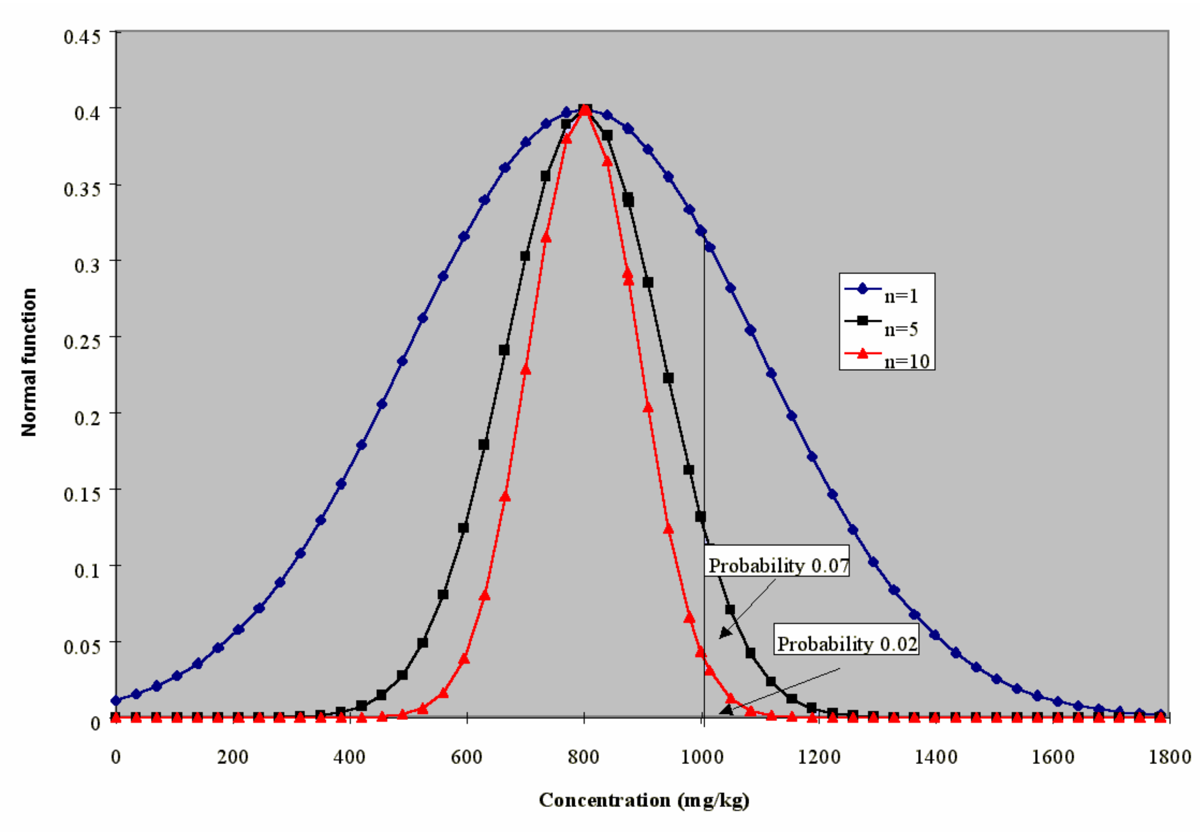

Figure C.3 **Reduction of uncertainty by an increase in the sample size**

C2.2.1 Optimal sample size

Figure C.4 illustrates how to prevent the error of not acting when decontamination should be carried out. In practice, the incorrect decision of acting when there is no need to do so must also be prevented.

Therefore, calculating the optimal sample size (*n)* requires determining an indifference zone and defining the probabilities of making an incorrect decision, including the probability of removing sediments when contamination is not present as well as the probability of not removing sediments when contamination is present. The probability of the former event can be set at 0.1 and that of the latter at 0.02, as shown in Figure C.3.

In summary, this calculation of sample size involves respecting the following conditions:

- An indifference zone between 800 mg/kg and 1000 mg/kg.

- A 10% probability of removing sediments when the actual contaminant concentration is no more than 800 mg/kg.
- A 2% probability of not removing sediments when the actual contaminant concentration is at least 1000 mg/kg.
- The results of the calculation lead to the determination of a critical decision value above which the decision-maker must decide to remove the sediments and to the definition of an optimal sample size.

The results are shown in Figure C.4.

The critical value is 880 mg/kg and the required sample size is 25. If the analysis of 25 subsamples led to results greater than 880 mg/kg, the sediments would be removed, while no action would be taken if the results were below this value. If the result is 880 mg/kg or more, there is a 10% chance that the actual contaminant concentration is 800 mg/kg or less; therefore, the chance of making the error of removing the sediments when unnecessary is 10%. If the result is below 880 mg/kg, there is only a 2% chance that the actual concentration will be 1000 mg/kg or more. Since, in this case, the decision rule dictates that no action should be taken, there is a 2% chance of making the error of not acting when the sediments must be removed.

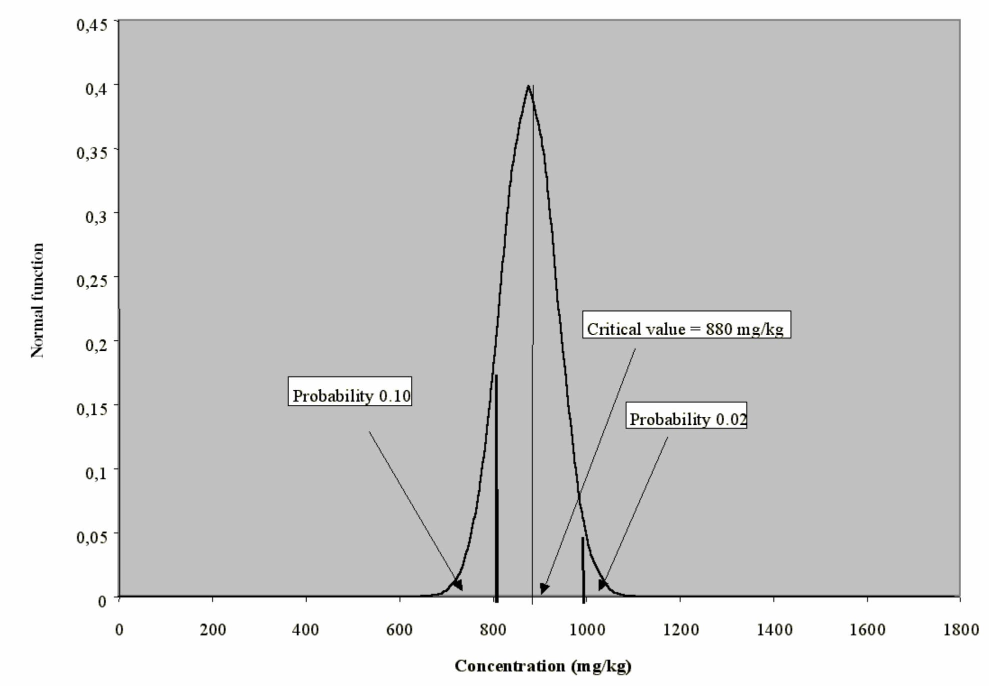

Figure C.4 Optimal sample size according to classical statistics

This information is summarized in the decision matrix (Table C.2) below.

Table C.2
Decision matrix for action-state pairs

State of nature	**Action**	
	a_0 (do nothing)	**a_1** (remove)
e_0 Contamination < 880	**Correct decision**	Risk of error (P concentration = 1000 =0.02)
e_1 Contamination > 880	Risk of error (P concentration = 800 = 0.10)	**Correct decision**

C2.3 Interpreting the uncertainty reduction process

With this type of solution, the probabilities of making an incorrect decision have a tangible meaning because they express the risks accepted by the decision-maker based on the critical value. With all things being equal, the smaller the probability of these risks, the greater the result of the sample size calculation. On one hand, if the decision-maker perceives that the environmental risks are high, he or she will opt for the small probability of making the error of not removing sediments when they should be removed. On the other hand, if decontamination costs are high, the decision-maker will opt for a low probability of making the error of decontaminating when it is not necessary. These two variables give decision-makers the opportunity to express their preferences regarding the risks they are ready to accept, but do not allow them to take account of the sampling cost. The cost of acquiring additional information may be high enough or the cost of decontamination low enough that it is better to make an immediate decision.

This method also entails the arbitrary establishment of an indifference zone. Usually, the standard considered as the threshold of harm to the environment is used as the upper limit of this zone. The definition of the lower limit is arbitrary, however, and there are no criteria for defining it. The underlying assumption is that the decision-maker will wish to act if concentrations are equal to or greater than the upper limit, will have no preference for either action if the concentration falls between the two limits (the indifference zone) and will not wish to act if the concentration is less than the lower limit. With all things being equal, the narrower the indifference zone, the larger the sample size will be. This concept makes it difficult for decision-makers to express their preferences when cost is an important consideration in the decision. Intuitively, the decision-maker will opt for a narrow indifference zone and therefore a high sample size if sampling costs are low, but decontamination costs are not taken into account in the decision.

The calculation of the optimal sample size is therefore based on the definition of three variables: two probabilities of making an error and one indifference zone. The definition of the two probabilities is based on a fairly concrete notion but this is much less true for the definition of an indifference zone. Since the probabilities and extent of the indifference zone mutually influence the calculation of sample size, this makes it more or less impossible for decision-makers to intuitively select values that represent their budgets and contamination and decontamination costs at the same time.

In addition, when decision-makers are faced with several sampling projects, each with different costs and environmental implications, sharing resources efficiently among them is difficult if not impossible. For each project, three types of cost have to be estimated: sampling, decontamination, and the risk of making an incorrect decision. This is a complex problem that cannot be solved intuitively. Before looking at the solution offered by Bayesian mathematics, the following sections will discuss in greater detail the costs involved in environmental sampling that must be taken into account in decision-making.

C3 Costs Relevant to Environmental Decision-making

To ensure resources are efficiently allocated, Bayesian mathematics requires that costs be defined. A monetary scale appears to be the simplest to use since this scale is used to assess costs during sampling activities. However, any measurement scale could be used.

C3.1 Cost inventory

By definition, the sampling cost (including the cost of analyses and related activities) is already known. In Bayesian analyses, although it is necessary to know this cost in order to determine an optimal sampling strategy, the cost is not used in the first part of the study.

The costs of decontamination, restoration and treatment are usually known or fairly easy to determine. Usually, these costs are expressed in terms of a fixed amount for a given volume of sediments. In some cases, particularly for biological and chemical treatments, the cost may vary with the degree of sediment contamination. This document does not describe how to estimate such costs, but doing so is not particularly difficult.

The third cost is the economic cost, which corresponds to the losses to society due to environmental degradation. In the case of sediments, this cost could include such things as losses due to decreased fishery resources or decreased use of the river.

C3.1.1 Socio-economic aspects

In terms of social aspects, environmental protection is closely linked with an awareness of the consequences of pollution. A community agrees to allocate financial resources to controlling pollution because it realizes that there is a risk of environmental degradation, which may be accompanied by social costs, which are sometimes even higher.

First, in terms of social action, is the observation of the adverse effects of pollution on ecosystems. This observation results in the setting of standards on the maximum concentration of pollutants that the environment can bear, according to current scientific knowledge.

The economic cost consists of the financial resources that society agrees to allocate to control or reduce pollution. These costs have been partially documented in the literature although, according to some authors (Bente 1996), such data are inherently inaccurate. Several sources of bias have been noted in contingent and hedonistic evaluation (preference studies). In addition, there is sometimes a significant difference between the amount that individuals say they will pay and the actual amount they would pay if the state decided to act

(Kalle and Strand, 1992). During the last few years, the number of publications on the subject has mushroomed and there is an emerging consensus on various methodological aspects and empirical results. There are also many documents on the subject on the Internet, including the IJC Biennial Forum in Milwaukee (1999), Kopp et al. (1997), Sunstein (2001) and Krupnick et al. (2000).

Although the financial resources allocated by society to controlling pollution can provide a useful basis for determining total socio-economic costs, this method is not totally satisfactory when using Bayesian models. In practice, managers must be able to at least define the general magnitude of the economic costs of each environmental program they are managing.

C3.1.2 Valuation of economic costs

One way to assess economic costs is to use macroeconomic models, which, although they are not very precise, provide a rough estimate of the total economic stakes involved in pollution.

Figure C.5 shows a probable curve of economic costs as a function of the level of contamination. The exponential nature of the curve is associated with the fact that, in general, social costs increase very rapidly with the level of contamination. This graph is divided into four zones, each of which represents a different level of contamination.

Zone 1. Zone 1 characterizes a region that is relatively unaffected by pollution and in which the consequences on ecosystems are marginal. In this region, ecologists cannot demonstrate, using statistical methods, any cause and effect relation between observed phenomena and pollution, although some indices can be perceived.

Zone 2. In zone 2, scientists are able to identify effects on sensitive ecosystems, but the marginal contribution of pollution to a deterioration in human health, for example, is statistically insignificant. This zone includes regions that have not suffered significant damage.

Zone 3. In zone 3, statistically significant health problems are present. Epidemiological studies show more cases of bronchitis, asthma and cancer. In general, the health of the population is worsening and pollution has been identified as the main cause, with obvious effects on ecosystems. Scientists have identified several endangered species. This zone includes highly polluted cities, for example.

Zone 4. In zone 4, the problems identified in the previous zone are rapidly worsening. A significant decrease in life expectancy can be measured. Epidemiological studies show that the incidence of pulmonary diseases, cardiovascular problems and some types of cancer is clearly above the world average, even taking lifestyle into account. Sometimes, water quality has deteriorated to the extent that it has become one of the main causes of disease.

Similar models can be used to identify the standard costs associated with various types of contamination. Such costs are no doubt a reflection of the current state of economic knowledge, just as current pollution standards are representative of maximum tolerable levels for the environment according to current scientific knowledge.

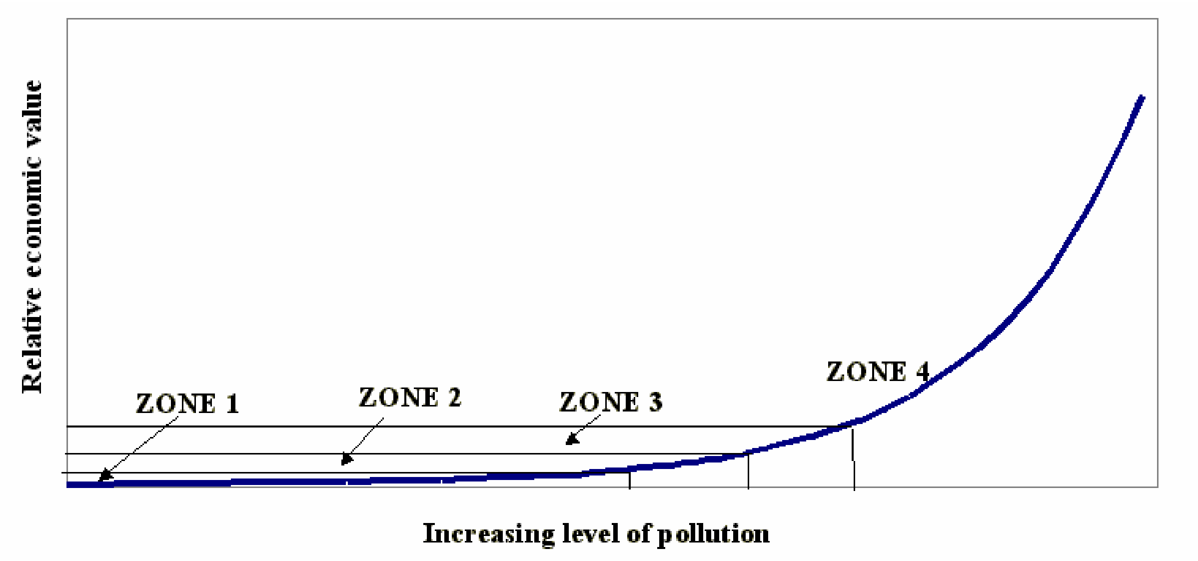

Figure C.5 Socio-economic value of damage caused by pollution

Using standard socio-economic data, Bayesian models allow a rational basis to be developed for standardizing the entire environmental action process, from information acquisition to decision-making. In the absence of data validated by the community, the manager can use two extreme values. The solution will entail two different results, which provide guidelines to assist in decision-making.

C3.2 The economic cost implicit in classical statistics

Although the notion of economic cost is not invoked in classical statistics, the notion of economic value is implicit in the decision-making methods used. For example, the concept of a standard represents the threshold beyond which action must be taken to protect the environment. When standards are exceeded, the act of intervening tacitly implies that the economic cost represents at least the cost of decontamination. If the contaminant is present at concentrations below the standard, the act of not intervening implies that the cost of the contamination is zero. From the outset, reality has been altered by this notion since costs generally increase with the level of concentration. The economic cost would not actually be zero if contaminants were present at concentrations slightly below the standard.

In addition, in any sampling strategy based on classical statistics, an implicit economic value associated with pollution can be demonstrated. This observation becomes more understandable when Bayesian models are introduced. When sampling and decontamination costs are known, the economic costs associated with contamination can be calculated based on the amount to be invested in obtaining additional information.

Unfortunately, ignoring economic considerations in sampling management can lead to various distortions, which can result in the inefficient allocation of resources.

C4 Bayesian Analysis

This section presents three examples of environmental problems that can be analysed using Bayesian mathematics. The expression of economic costs becomes progressively more refined with the three examples. In addition, one of the examples will be used to show how Bayesian mathematics can assist in planning an optimal sampling strategy.

C4.1 Fixed economic costs

The previous example illustrating the approach employed in classical statistics is used again in this section. In this case, however, costs are associated with the various action-state pairs. Fixed costs are used, not only to represent certain elements found implicitly in classical methods, but also to illustrate as simply as possible the logic of the Bayesian approach.

Table C.3 shows the costs associated with the various action-state pairs in this example. The items used in Table 2 to qualify decisions have now been replaced with actual costs.

Table C.3
Cost matrix for action-state pairs

State of nature	**Probability**	**Action**	
		$\mathbf{a_0}$ (do nothing)	$\mathbf{a_1}$ (remove)
$\mathbf{e_0}$ (Low level of contamination)	0.75	0	\$10,000
$\mathbf{e_1}$ (High level of contamination)	0.25	\$100,000	\$10,000

Action a_0, which consists of doing nothing, will be assigned a zero cost if state e_0 prevails (i.e. if contaminant levels are below 1000 mg/kg). Using a zero cost reflects the fact that, in classical statistics, there is no action when concentrations do not exceed the standard.

However, if sediments are in fact contaminated, substantial costs could result if no action is taken. If pollutant concentrations exceed the standard and no action is taken (pair a_o-e_1), the cost could be assumed to be around \$100,000. This cost corresponds, for example, to a reduction in fish or shellfish stocks or long-term effects on human health. Lastly, the cost of sediment decontamination is \$10,000 and this cost remains the same regardless of contaminant concentrations. The overall problem is shown in Figure C.6.

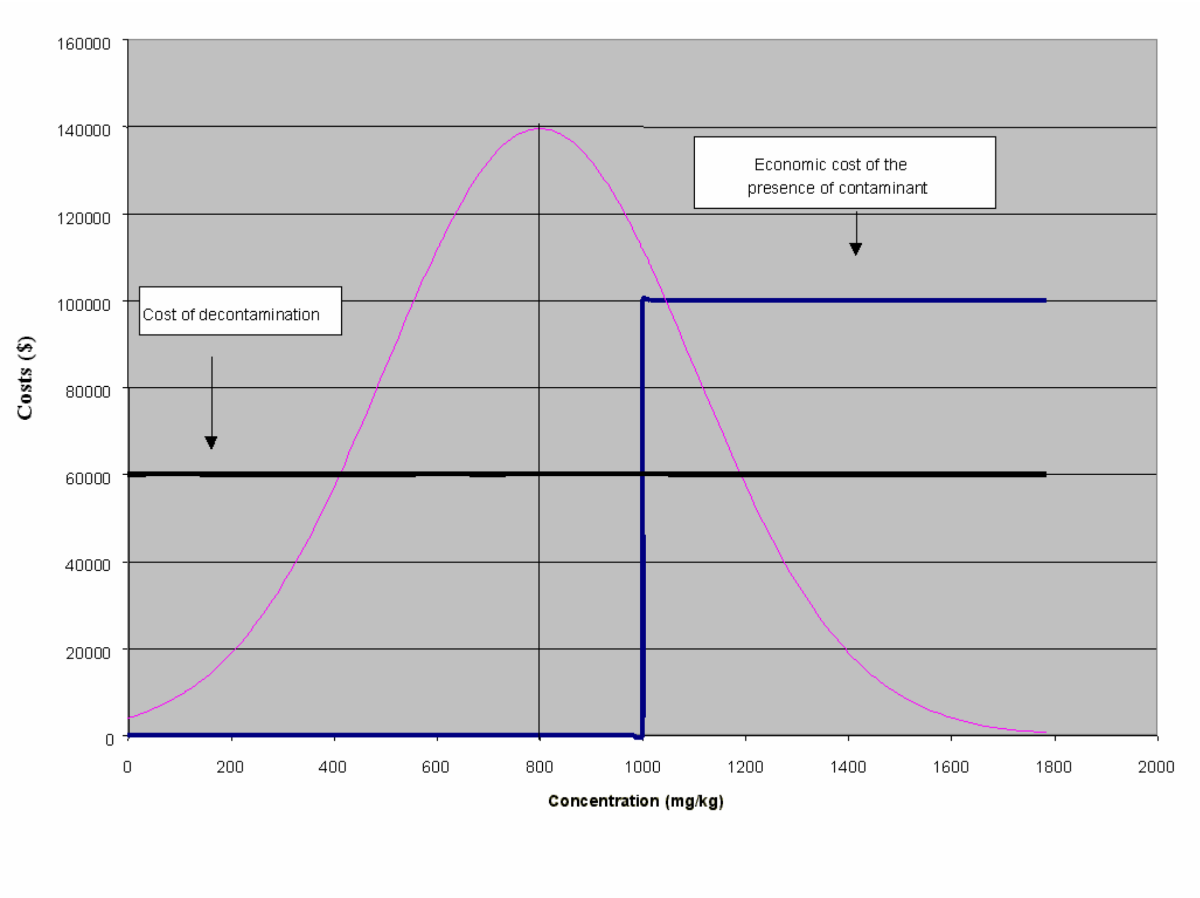

Figure C.6 **Cost of pollution as a function of the level of contamination**

C4.1.1 Calculation of regret

The decision to decontaminate (a_1) will result in a waste of resources should concentrations fall below the standard (state e_0), since money will be invested in vain. If, after decontamination, it can be stated unequivocally that the sediments were not contaminated, the manager will "regret" having made the investment.

The regret is therefore linked to an incorrect decision that resulted in unnecessary costs and left the manager feeling that he or she had wasted resources. If the manager had known exactly what the state of nature was, he or she could have made the correct decision. Bayesian analysis uses this notion of regret in the calculation process.

The reasoning behind regret calculations is as follows: if contamination levels are below the standard and the decision is made to decontaminate, one will waste, or regret having spent, the amount of $10,000. On the other hand, if contamination levels are high and the decision is not to act, one will regret the difference between $100,000 (the cost to society of not decontaminating) and $10,000 (the cost of decontaminating).

Although regret can be evaluated on a case-by-case basis by using the previous line of reasoning, it is easier to calculate regret by using a simple arithmetic operation on the cost matrix shown in Table C.3. The value of regret is obtained by taking, for a given level of concentration, the lowest amount ($) in the cost matrix and subtracting this amount from the cost of each alternative (e.g. high levels of contamination: 100,000 – 10,000 = 90,000 and 10,000 – 10,000 = 0). The results are shown in Table C.4. It should be noted that the result of the operation is always positive.

Table C.4
Regret matrix for action-state pairs

State of nature	**Probability**	**Action**	
		$\mathbf{a_0}$ (do nothing)	$\mathbf{a_1}$ (remove)
$\mathbf{e_0}$ (Low level of contamination)	0.75	0	$10,000
$\mathbf{e_1}$ (High level of contamination)	0.25	$90,000	0

C4.1.2 Cost of uncertainty

The last step in the calculations is to multiply each element in the matrix by the associated probability, which gives the expected regret (mean of regrets taking account of probability) for each action (Table C.5). The action retained is the one with the smallest regret. In this case, the minimum expected regret is $7,500 and the decision-maker should opt for decontaminating the site (a_0). Intuitively, this is the decision that many managers would have opted for, given a 25% probability of the standard being exceeded. In actual fact, however, it depends on the economic costs of leaving the contaminants in place. If managers perceive that the environmental cost will be low, their intuition may lead them to decide not to act. A typical example involving low and high economic costs is PCB-contaminated soil located in a desert and near a residential neighbourhood, respectively. The advantage of this approach is that the consequences of contamination are expressed quantitatively, with a simple calculation providing a solution. When accurate economic costs are not available, mangers can use minimum and maximum costs and determine if the optimal action remains the same.

Table C.5
Matrix of expected regrets for each action

State	Probability	Action	
		A_0 (do nothing)	a_1 (remove)
e_1	0.75	0	\$10,000
e_2	0.25	\$90,000	0
Expected regrets		\$22,500	\$7,500

The minimum expected regret (\$7,500) not only points to the best decision but also represents the maximum sum that can be invested in sampling before a final decision has to be made. It is designated either as the "**cost of uncertainty**" or the "**expected value of perfect information (EVPI)**".

Figure C.7 illustrates the cost of uncertainty for different probabilities of contamination. This graph was obtained by calculating the expected regret for a range of probabilities between 0 and 1 that contamination is above the standard.

The cost of uncertainty will be zero if the probability of contamination is 1 (see righthand side of the graph). If the mean result is around 1900 mg/kg (1000+3σ), the probability that pollutant concentrations will be above 1000 mg/kg is certain; therefore, removal is the correct decision, since uncertainty and cost are zero. Moving toward the lefthand side of the graph, the cost of uncertainty increases. The point used as our example is found here (\$.25–\$7,500). This cost increases until it intersects with the function of the cost of doing nothing. At this point, the cost of uncertainty for each action is the same. Subsequently, as one moves further left, the cost of uncertainty for doing nothing becomes less than the cost of removal.

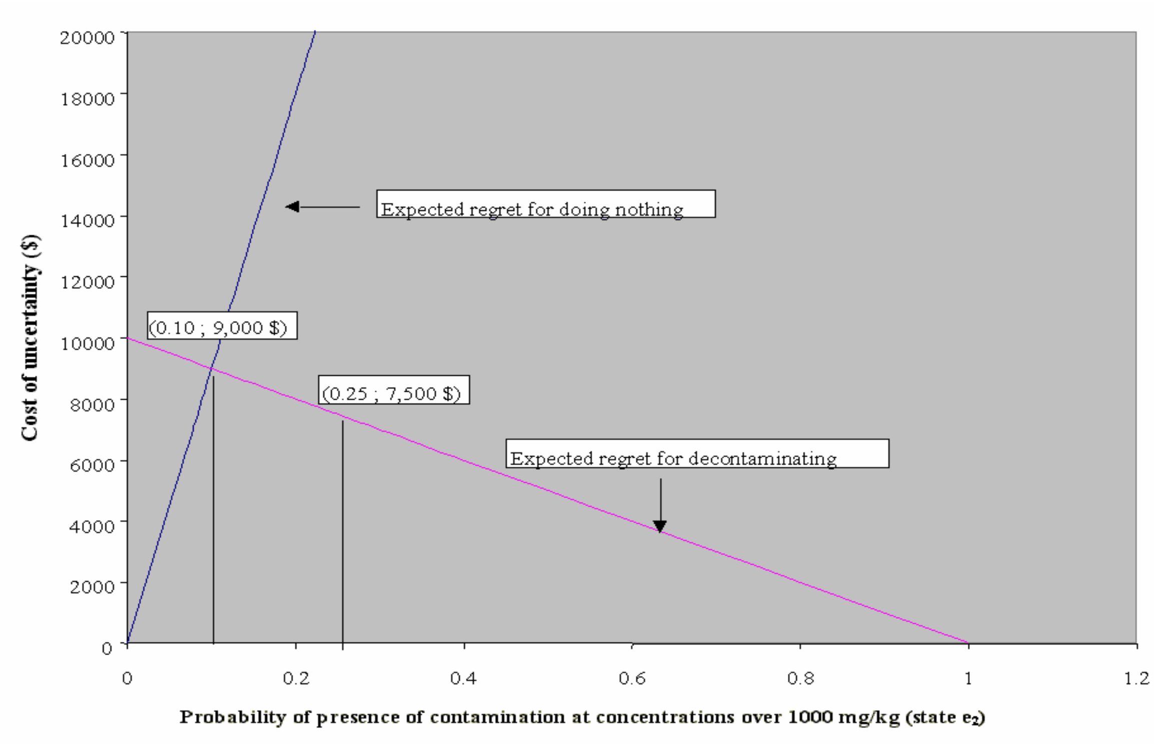

Figure C.7 **Cost of uncertainty for each action as a function of the probability of exceeding the standard**

According to the data, the manager should opt for removal if the probability of concentrations equal to or greater than 1000 mg/kg is 0.10 or more and should opt for doing nothing if the same value is below 0.10. To satisfy these conditions, the mean concentration must be around 610 mg/kg with a standard deviation of 300 mg/kg.

C4.2 Cost expressed with a linear equation

The previous example will be used again, replacing the fixed cost due to the presence of contamination by a linear function that shows the cost rising as contaminant concentrations rise. It can be assumed that, if the sediments are not removed, the function of the cost of contamination can be expressed with the following equation:

$$y_1 = 100\,x$$

Where y_1 represents the economic cost of the effects of contamination in the sediment zone on the environment and x represents the concentration of pollutants in mg/kg.

Furthermore, assuming that the dredging and decontamination costs are $60,000, consequently:

$$y_2 = 60{,}000$$

The distribution curve is identical to the one in the previous example. Figure C.8 summarizes the characteristics of the problem:

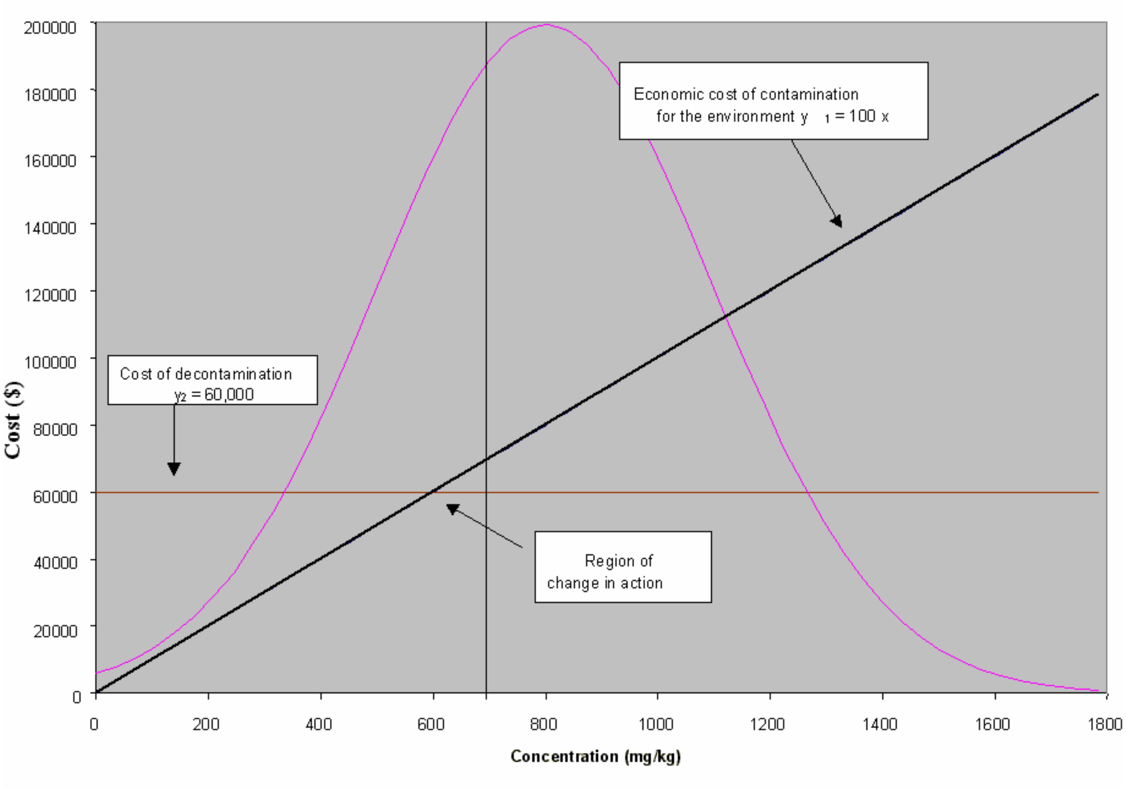

Figure C.8 Cost of pollution as a function of level of contamination

At a mean concentration of 800 mg/kg, the optimal action is decontamination. As the graph shows, both actions have equivalent costs at the intersection of the two lines $y_1 = 100\,x$ and $y_2 = 60{,}000$. Consequently, at a contamination level of 600 mg/kg, decision-makers would have no preference between removing and leaving environmentally harmful contamination. This is the break-even point or indifference point. Therefore, the optimal actions are to:

- Remove contaminant if the mean concentration is 600 mg/kg or more.
- Do nothing if the concentration is below 600 mg/kg.

C4.2.1 Regret functions

The regret functions are provided by the following equations:

$$\begin{aligned} R_{\text{do nothing}} &= 0 \text{ if } x \leq 600 \text{ mg/kg} \\ &= 100\,x - 60{,}000 \text{ if } x > 600 \text{ mg/kg} \\ R_{\text{decontaminate}} &= 0 \text{ if } x \geq 600 \text{ mg/kg} \\ &= 60{,}000 - 100\,x \text{ if } x < 600 \text{ mg/kg} \end{aligned}$$

These equations are shown in Figure C.9.

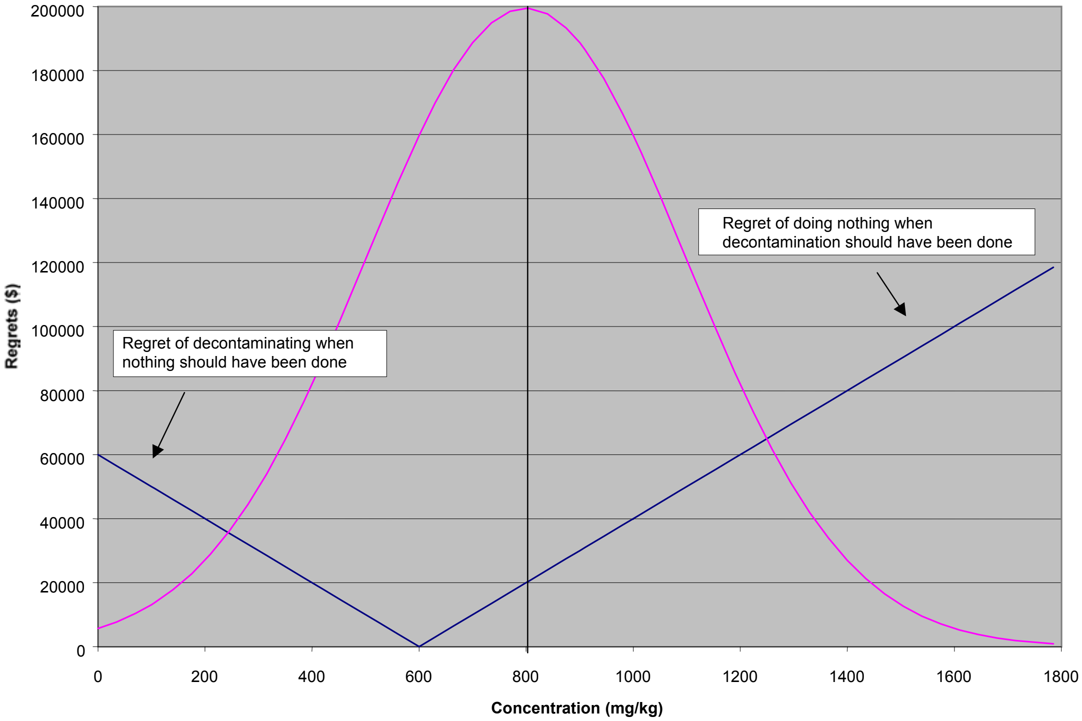

Figure C.9 Regrets for actions based on contamination level

C4.2.2 Cost of uncertainty

The expected value of perfect information (EVPI) can be obtained with the following equation, which makes use of the loss function for the reduced centred normal:

$$EVPI = \left| B_2 - B_1 \right| \sigma \, Ln \left| \frac{e^0 - \mu}{\sigma} \right| \qquad \textbf{Equation 1}$$

Where B_2 and B_1 are the slopes of the two cost functions, μ and σ, the mean and standard deviation and e^0, the indifference point. *Ln* represents the loss function for the reduced centred normal and ranges between 0 and 0.4. The difference between the slopes—in our example, 100 mg/kg—and the standard deviation for the population are the most important factors in determining the cost of uncertainty.

With a mean of 800 mg/kg, the EVPI is $4,500. This suggests that it may be cost effective to spend no more than this amount to obtain additional information. This issue will be looked at in greater depth in the following section.

Figure C.10 shows the cost of uncertainty (EVPI) for different values that could have been obtained for the sample mean, with all other things being equal.

The maximum value of the cost of uncertainty could have been reached if the mean result of sampling had been 600 mg/kg, which is the indifference point for the two actions. Intuitively, this result can be explained by the fact that the risks of making an incorrect decision are the highest at this point, as are costs. In fact, at mean concentrations of 600mg/kg, managers may very well decide to remove the contaminated sediments at a cost of $60,000 when concentrations are actually quite a bit lower. As the standard deviation of 300 mg/kg for the distribution shows, precision is rather low in this example. Conversely, it is also easy to make the error of not removing the sediments when concentrations result in damage over $60,000.

C4.3 Sampling strategy

The Bayesian approach also provides a methodology for assessing the cost-effectiveness of carrying out further sampling to reduce uncertainty. The purpose of this section is to examine some of the results that can be obtained with additional sampling through a simulation. An *a priori* and *a posteriori* analysis is used in the simulation to assess, among other things, whether pursuing additional sampling operations is worth the cost, taking account of the additional costs of the new tests.

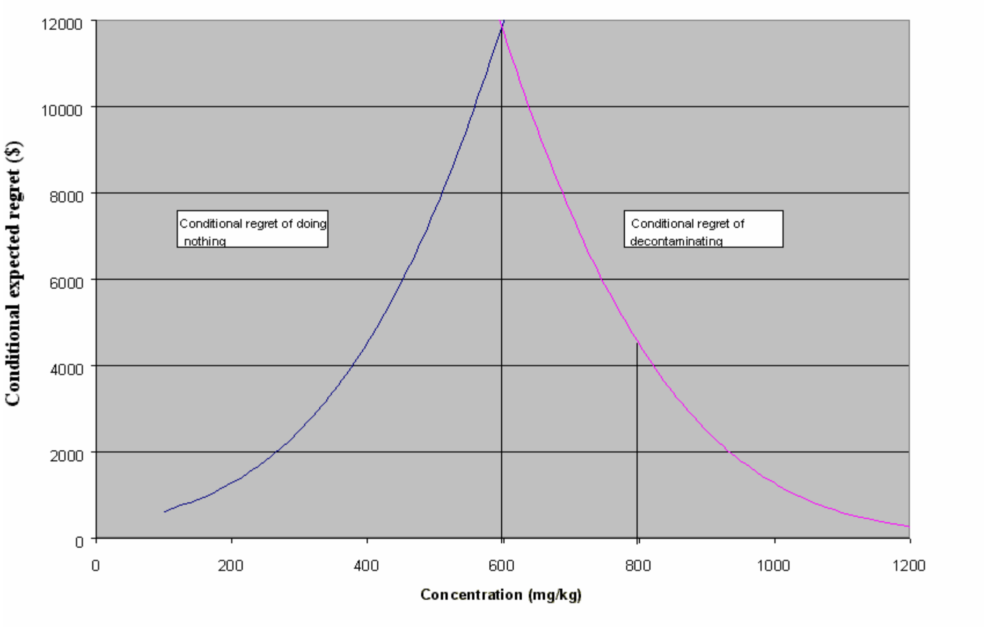

Figure C.10 **Conditional expected regrets as a function of mean contaminant concentrations measured in the sediment**

C4.3.1 Combining information from different sampling operations

A sampling operation provides information characterized by a mean and a standard deviation; the larger the sample size, the more precise the information. When the information obtained from a current sampling operation and any information obtained through additional sampling is combined, the total information obtained can be expressed in the following equation:

$$I_1 = I_0 + I_X$$

Where I_1 represents total information, I_0, the current information and I_X, the information from the new sample.

The new information can also be characterized by a mean and a standard deviation. The new mean can be estimated using the following equation:

$$\mu_1 = \frac{\frac{1}{\sigma_0^2}\mu_0 + \frac{1}{\sigma^2/n}\bar{x}}{\frac{1}{\sigma_0^2} + \frac{1}{\sigma^2/n}} \qquad \textbf{Equation 2}$$

Equation 2 expresses the overall mean by weighing the a-priori mean μ_0 using the mean from the new sample ($\bar{x}$). The mean for the new sample is weighted by its size using the factor n, unlike the mean for the current information μ_0, which is not. This part of the equation $(\mu_0/\ \sigma_0^2)$ expresses the fact that the standard deviation for the population (σ_0) is known. In the proposed solution, the standard deviation for the sample was estimated to be 300 mg/kg and no sample size was hypothesized; consequently, $n = 1$. The equation takes account of the quality of information obtained. If the *a priori* information was poor, the standard deviation (σ_0) would be large and the mean μ_0 would have little weight in the calculation of the overall mean μ_1, as long as the new sample is relatively large.

The following equation is used to combine the standard deviation for the two types of information. The aggregation process used is similar to the previous one, with the sample size affecting the importance of each contribution in the calculation of the overall standard deviation.

$$\frac{1}{\sigma_1^2} = \frac{1}{\sigma_0^2} + \frac{1}{\sigma_{\bar{x}}^2}$$

This can be rearranged as:

$$\sigma_1^2 = \frac{\sigma_0^2 \sigma^2}{\sigma^2 + n\sigma_0^2} \qquad \text{where} \qquad \sigma_{\bar{x}}^2 = \frac{\sigma^2}{n} \qquad \textbf{Equation 3}$$

Equation 3 allows the precision of the information in the two samples to be expressed quantitatively.

C4.3.2 Application

Figure C.10 shows the value of the cost of uncertainty for the various mean concentrations that could have been obtained with the sample. At 800 mg/kg, the cost is $4,500. However, the EVSI varies according to the mean obtained. Consequently, if the actual mean is something other than 800 mg/kg, this would have a significant impact on the initial cost of uncertainty and therefore on the maximum amount that could be invested in sampling. With this method, the user must keep in mind that if the original information is biased, the investments thought to be required will be over- or underestimated.

The pre- and a-posteriori analysis requires a hypothesized value for the mean of the next sample. If the preliminary information is credible, it is reasonable to believe that this mean will be around 800 mg/kg. This hypothesis represents the best compromise or maximum likelihood given the available data.

Hypotheses concerning sampling costs comprise:

- $500 for the sampling team
- $25 for each sample and mixing under conditions that ensure representativeness. A single sample will be analysed but may consist of several subsamples
- $200 for analysing the sample.

Under these conditions, the variable costs are $25, fixed costs are $700 and the function of cost and analyses is expressed in the following equation:

$$y_4 = 700 + 25x$$

The next analysis entails simulating the addition of successive samples and calculating the standard deviation for each new sample using equation 3. The reduction in the standard deviation associated with the additional sampling helps to reduce uncertainty. The new information is designated as the expected value of sample information (EVSI). Subtracting the sampling cost from the EVSI provides the expected net gain of sample (ENGS). An increase in the expected net gain indicates that additional sampling will be cost effective. Table C.6 shows the results.

Table C.6
Reduction in uncertainty as a function of sample size

Calculation of expected net gain					
n	***a priori* EVPI**	**EVSI**	***a posteriori* EVSI**	**Cost**	**ENGS**
2	4500	3422	1077	750	2673
4	4500	4097	402	800	3297
6	4500	4319	181	850	3468

8	4500	4420	80	900	3520
10	4500	4455	45	950	3504

The net gain increases along with the sample size until the latter reaches eight, and then falls off. This information is summarized in Figure C.11, which confirms that the curve of the net gain has a negative slope after eight samples.

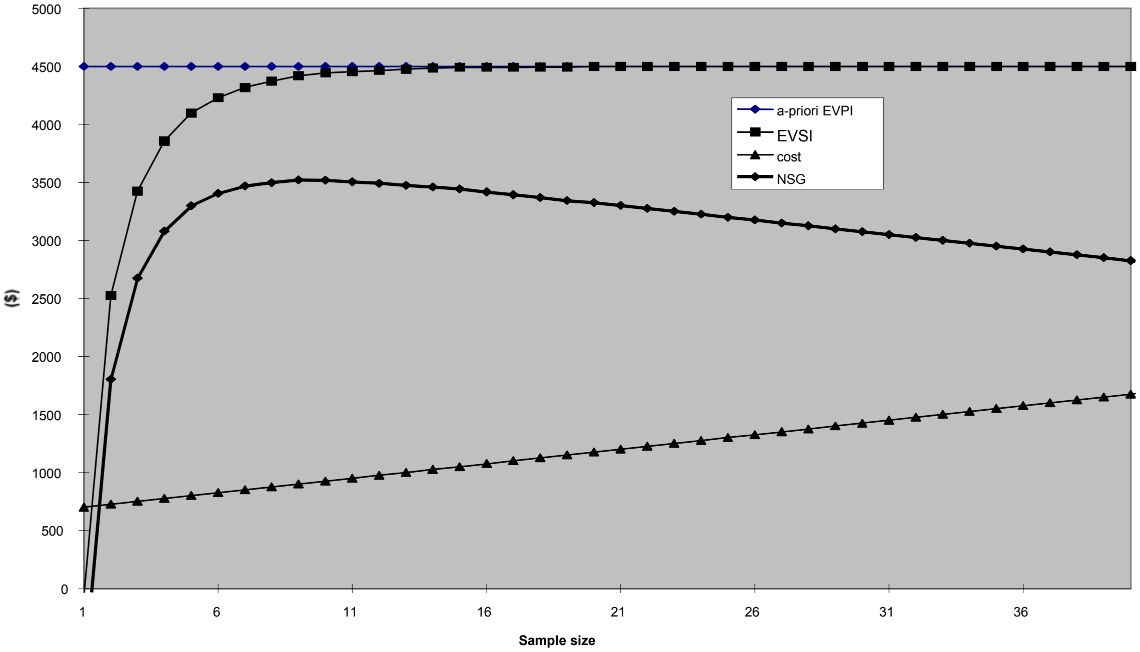

Figure C.11 Expected net gain as a function of sample size

Consequently, the optimal strategy is to use a sample size of 8. In this example, the cost of uncertainty decreases rapidly with sample size since the expected mean from additional sampling was fixed at 800 mg/kg, a point where uncertainty is relatively low. The result of the sample size calculation would be much greater if the *a priori* and *a posteriori* mean had been fixed at 600 mg/kg, for example, where uncertainty is much greater.

When the additional sampling has been carried out, the information obtained is combined using equations 2 and 3. The new mean and standard deviation provide a starting point for carrying out a new *a priori* and *a posteriori* analysis and the same process is used to determine if obtaining more information is cost effective.

C4.4 Expression of costs using linear equations

Although a variable cost function represents an improvement over fixed costs, the reasoning behind the choice of the least expensive alternative is somewhat problematic. Choosing an optimal action solely on the basis of the notion of minimum cost results in the possibility that the action of doing nothing can be chosen even when concentrations are well above the standard. Figure C.12 illustrates this problem.

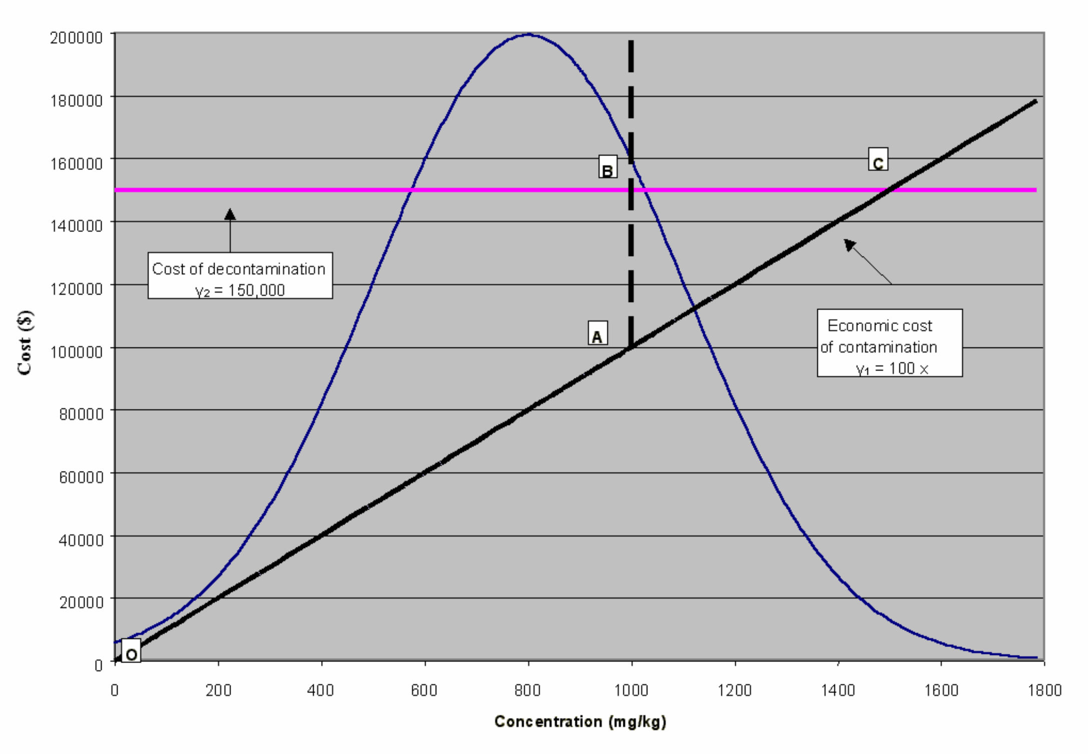

Figure C.12 **Problem of a decontamination cost being greater than an economic cost**

In this example, the fixed decontamination cost is $150,000. Point C is the intersection of the line for fixed costs and the line for economic costs ($y = 100\ x$). Based solely on the notion of minimum cost, the manager should do nothing until concentrations reach 1500 mg/kg. The economic costs of contamination only become greater than decontamination costs at point C, in other words for concentrations over 1500 mg/kg. The notion of a standard, however, implies that managers must act when concentrations reach 1000 mg/kg.

Several mathematical functions can be used to represent this problem. The most radical solution is to add a cost function with an infinite slope when concentrations reach 1000 mg/kg. Therefore, as shown in the graph, instead of solving the problem by using the segment OAC, the segments OAB are used (AB is shown as a dotted line on the graph). This model suggests that serious economic consequences will be observed when concentrations exceed the standard. Less serious consequences could be represented by a more or less pronounced change in the slope around the standard or by using an exponential function.

In this section, the previous example will be reintroduced with a steeper slope for the cost function when concentrations exceed the standard. The functions used include:

For contaminant concentrations of 0–1000 mg/kg:

$$y_1 = 100\,x$$

For concentrations over 1000 mg/kg:

$$y_2 = 500\,x - 400{,}000$$

The decontamination cost is represented by:

$$y_3 = 90{,}000$$

All the other data in the problem are the same; Figure C.13 gives an overview of the problem.

It can be observed that the actions are equivalent at the intersection of the two lines $y = 100$ x and $y = 90{,}000$. Consequently, no preference would be shown for either removing or leaving the contamination when concentrations are around 900 mg/kg, which is the break-even or indifference point. *A priori*, by using only the notion of minimum cost, the optimal action is to do nothing if mean concentrations are 800 mg/kg. Therefore, the optimal actions are:

- Remove the contamination if mean concentrations are 900 mg/kg or more.
- Do nothing if concentrations are below 900 mg/kg.

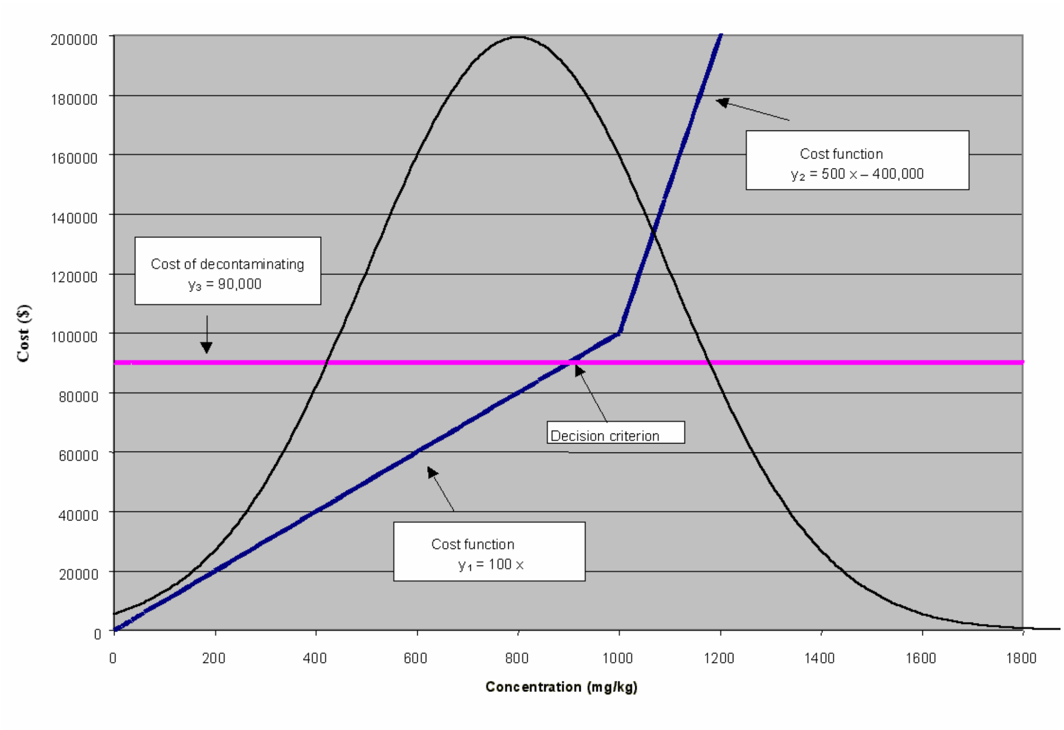

Figure C.13 Cost of pollution as a function of level of contamination

C4.4.1 Regret functions

The regret functions are obtained with the following equations and are shown in Figure C.14.

$$
\begin{array}{lll}
R_{\text{do nothing}} & = 0 & \text{if } x \le 900 \text{ mg/kg} \\
 & = 100\,x - 90{,}000 & \text{if } 900 < x > 1000 \text{ mg/kg} \\
 & = 500\,x - 400{,}000 - 90{,}000 & \text{if } x > 1000 \text{ mg/kg} \\
R_{\text{decontaminate}} & = 0 & \text{if } x \ge 900 \text{ mg/kg} \\
 & = 90{,}000 - 100\,x & \text{if } x < 900 \text{ mg/kg}
\end{array}
$$

C4.4.2 Cost of uncertainty

The cost of uncertainty is evaluated by integrating the normal curve and using the appropriate regret functions in each of the three regions. Given mean concentrations of 800 mg/kg, this cost is $18,075.

Figure C.15 shows the cost of uncertainty for different values of the mean for the preliminary result.

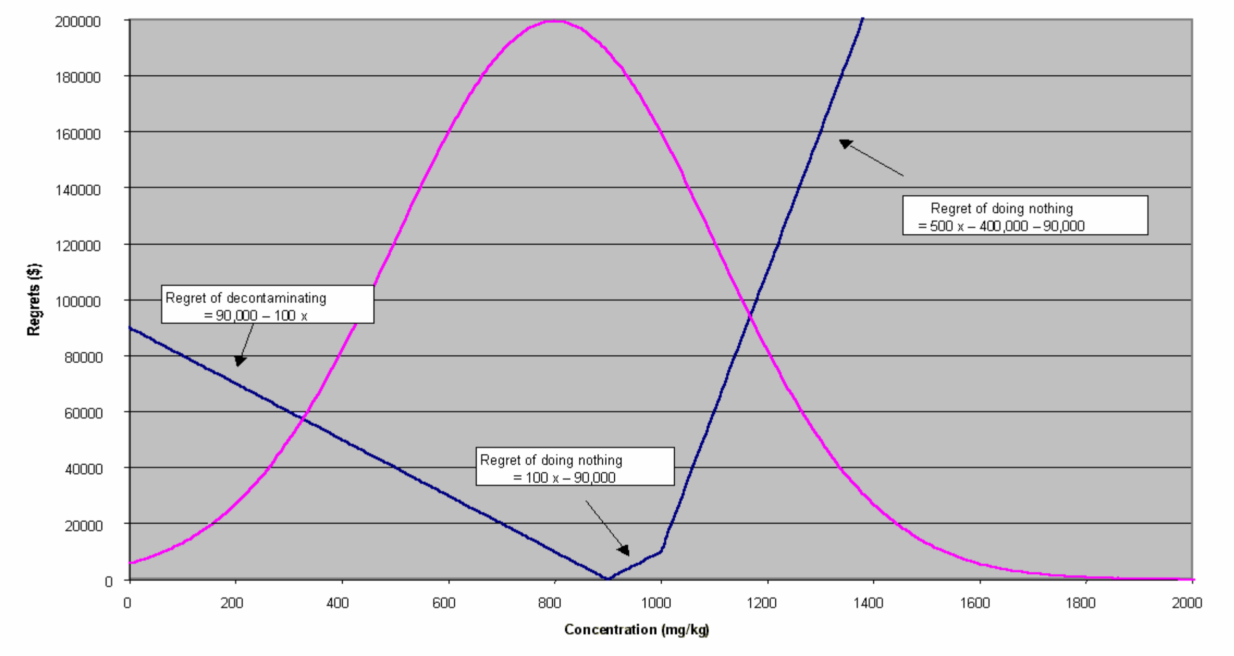

Figure C.14 Regret as a function of level of contamination

The maximum cost of conditional uncertainty is around $20,800. This result is obtained at a concentration of 761 mg/kg. This result is significantly different from the solution to the previous problem, where only one linear function was used. As seen previously, Figure C.10 confirms that the maximum cost of uncertainty is reached when the decontamination cost is equal to the cost of leaving the contamination in place, or the indifference point. In actual fact, when linear cost functions are used, the maximum conditional regret is always located at the indifference point.

In this example, the maximum cost of uncertainty should be observed at concentrations of 900 mg/kg instead of 761 mg/kg. This is due to the change in the slope for cost functions, resulting in a new indifference point at a lower concentration. This result makes sense given the problem at hand. If costs increase rapidly with the concentration, the manager should decide to decontaminate at a concentration below the indifference point.

Consequently, if the mean concentration obtained during preliminary tests is 800 mg/kg, the optimal decision is to decontaminate with a cost of uncertainty of $18,075.

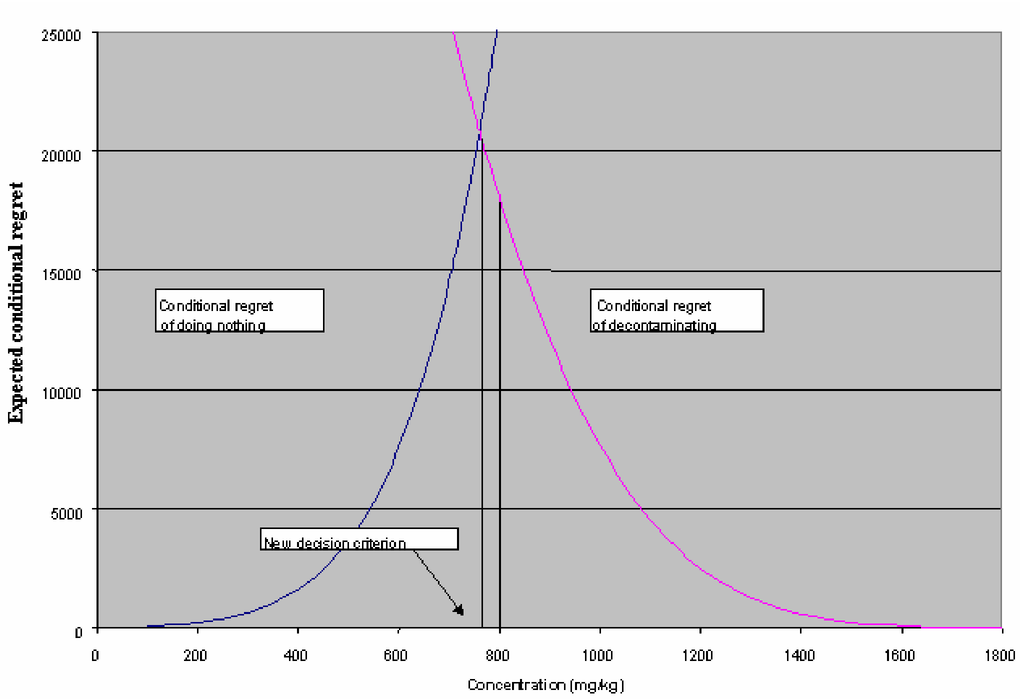

Figure C.15 **Conditional expected regrets as a function of mean contamination measured in sediments**

When costs are expressed with several linear functions or an exponential function, the choice of the optimal action is no longer determined by the intersection of the cost functions. Therefore, the conditional expected regret function for each action must be calculated and the intersection of the regret functions must be used to determine the new indifference point.

C5 Conclusion

In comparing the classical and Bayesian approaches, this document shows a number of significant differences between these two methods of evaluating stochastic processes. The Bayesian approach does not require the definition of an indifference zone. In classical statistics, this definition is essential, but the resulting representation is problematic.

Indeed, it could be demonstrated that social costs are implicit in all sampling based on classical statistics. When the sampling and decontamination costs are known, one can determine at which economic value for the environment a given strategy should be used. The approach proposed in this document deals with this issue in the opposite way. Despite a sometimes limited knowledge of the economic costs, by using Bayesian mathematics, decision-makers are able to use this economic cost information rather than having to ignore it completely and rely on notions of probability that can lead to decisions that are not representative of social values.

Although both techniques employ the notion of probability, the Bayesian method incorporates financial considerations, which are omnipresent in any environmental decision. Consequently, it provides managers with better decision support by promoting a better allocation of resources, not only to a single project but among many different projects. Lastly, since this approach allows the entire sampling approach to be structured, when standardized economic data are incorporated, a complete information synthesis and decision-making system can be created.

C6 Epilogue

This brief introduction to Bayesian mathematics shows that, by integrating economic functions into a statistical formulation, a fundamental analysis method that facilitates decision-making can be obtained. Unfortunately, this is only an appendix and not a full book, in which a number of related subjects could be discussed in greater depth at the chapter level to obtain a fully integrated whole.

To reveal the common thread between classical and Bayesian statistics and introduce the notion of the economic function, we have deliberately limited, if not omitted completely, the examination of a number of related subjects. A more in-depth study of these aspects, of course, would have provided a more faithful picture of the complexity of environmental sampling and allowed for the use of more diversified mathematical tools. However, widening the scope of the discussion would have made it more difficult to present the essential points of Bayesian mathematics and its environmental implications. The only relatively complex discussion undertaken was the formulation of economic functions. Therefore, readers should not be surprised if they do not find all the necessary ingredients for solving a specific sampling problem. This does not mean that solutions are not possible but that the solution must be adapted to the specific circumstances, using the tools appropriate for each task.

The purpose of this epilogue is to position the appendix in a broader context and to respond briefly to some comments received during a review of the document.

Economic cost function. There is very solid evidence (if not total certainty, at least a high degree of probability) for the aptness of the exponential representation used here, which resulted from the examination of economic issues. This result does not appear to have been documented yet in the literature, however. The definition of economic functions does not seem to be wishful thinking, given recent articles on the subject and the speed at which environmental applications are being developed.

Two important points are associated with this issue and should be emphasized without going into great detail. This is a highly complex subject, given the many notions associated with it.

The first point is the overall appearance of the economic cost diagram, the main characteristics of which are the measurement scale and degree of growth. These aspects depend on the level of economic development and the state of knowledge in a society. Different societies (with distinct cultures, lifestyles, collective wealth, degree of industrialization, etc.) should be expected to have different diagrams. However, this does not preclude the possibility that a given diagram could be representative of large populations. For example, given the similarity of the economic and social systems of the states, provinces and territories in North America, a single diagram may very well be suitable for the entire continent. Although collective wealth varies by region, government mechanisms act to uniformly distribute collective social costs and pollution should not be an exception, particularly since it is often transboundary in nature.

The other component of the economic function is the nature of the contamination found at a given site. For example, pollutants found in a mining region are different from those associated with agriculture. For each contamination problem, effects must be integrated and the results must be expressed in the form of a monetary cost scale. This integration can be carried out through a risk analysis based on toxicological and ecotoxicological assays.

Such studies are common at the moment and results can be expressed in a deterministic or probabilistic form; the resulting associated economic cost function has a similar character. For probabilistic studies, mathematical problem-solving requires mathematical tools that are quite a bit more sophisticated than those described in this document. This type of analysis consists of two random variables; the joint distribution function must be determined. Although probabilistic and deterministic approaches are basically comparable conceptually, the level of mathematical complexity in the former is clearly greater.

Hypothesis used. Another point raised concerns two hypotheses in the appendix that are highly unlikely to be found in the real world.

The first, already referred to, is the lognormal distribution of environmental observations. The methods of calculation used with the normal distribution are unchanged, except that with a lognormal distribution, the mathematical expressions used are more complex and the formulation is less intuitive.

The second hypothesis involves the interpretation of variance used in the examples. In practice, most sediment sample data are correlated, in other words, there is a trend towards an increase or decrease in concentrations in a given direction. This spatial correlation results in increased variance, due to the inclusion of an element of covariance. Uncertainty depends solely on random sampling errors and not on effects associated with progressive increases or decreases. All the examples, including the one involving the calculation of the optimal size of an additional sample, were developed based on the assumption that the variance does not include elements of covariance.

As discussed in Section 3.2.3.2, such correlations can easily be eliminated by mixing samples, although this may prove undesirable in practice. This issue was not discussed in depth in this guide and to deal with it completely would require a fairly long discussion involving a number of notions requiring a training in statistics or geostatistics. If required, a statistician should be engaged for the calculation or estimation of the sampling variance to eliminate correlation effects.

Cost function used to calculate optimal sample size. The last point involves the calculation of the optimal sample size. Here, the problem is presented so that, after the results of an initial sampling campaign are analysed, additional samples are taken in the field. However, the current practice is to take supplementary samples during the initial campaign and carry out additional analyses if required[10]. The issue is representing this situation mathematically.

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[10] This approach assumes that one knows in advance which area or areas are associated with uncertainty. In practice, the situation is usually quite varied. A typical example is a very contaminated sector, next to another zone where there is uncertainty about whether the standard is being exceeded, followed by a third area with very little contamination. In practice, only the area with uncertainty need be reexamined; returning to this site alone rather than taking additional samples in all the zones can be an advantage, depending on the costs involved.

The definition of the sampling and/or analysis cost function depends entirely on the situation. If additional samples are planned without any preliminary information being available, the uncertainty and economic cost functions must be estimated. Under these conditions, the sampling cost function will be limited to elements strictly involving sampling such as collection, transportation and the storage of containers. Even if zalculations are based solely on suppositions, it can still be useful to have an idea of the result in order to obtain a realistic picture of the number of additional samples needed.

If there is still uncertainly after an initial examination of the results, the optimum sample size should be recalculated using the analysis cost. It is important to note that sampling costs per se are no longer relevant in this scenario since the costs were already included in the previous step.

Regardless of the situation, therefore, the appropriate sampling cost functions can, due to the very nature of the process itself, be determined.

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