Sampling plan criteria for the bottom mud characterization of a drainage channel

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Abstract

Optimisation of sampling is a well known and solved problem in case of a classical mining project. In case of an environmental project, as is the sludge selection of a drainage channel, the problem looks like more complex. Indeed, the problem is conjugating the selection support dimension, the sampling density, and the estimates precision, with a benefit function which is not anymore a simple cost analysis. In fact it is necessary to give an economic meaning to the cut-off values defined by the local laws, values which vary depending on the element.

The paper presents such analysis in the case of a drainage channel of Padana Plane in Northern Italy to be dredged for routine maintenance. The specific question is the choice of mud correct destination among the several solutions available, depending on the element mean values of selection units.

The analysis moved from the results of a classical Geostatistical processing based on the available sampling. A critical revision of national and regional regulation on this and similar matters, coupled with the contribution given by the geostatistical estimating approach to risk analysis, allowed to identify some proposal for a cost function definition, linked to the estimates incertitude. The support effect and other estimating parameters showed to play the expected relevant role. The indeterminateness of actual regulations and the opposed interests between drain administrator and public concern, make more complex the identification of a general methodology for sampling plan and selection support optimisation. The results put in evidence the need of an improvement of UE regulation.

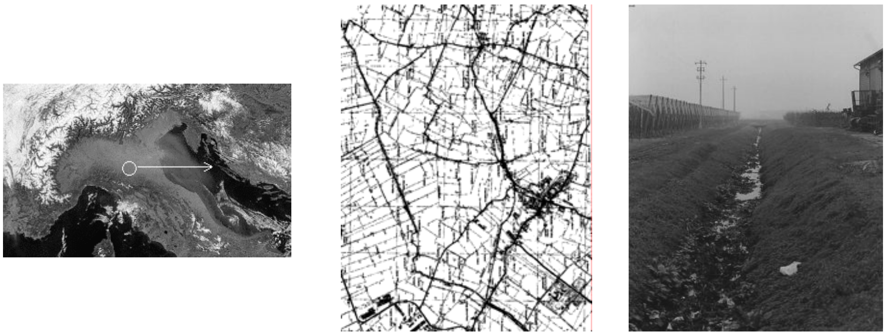
Introduction

The Italian planes are characterized by artificial channel nets which carry the meteoric water, avoiding stagnation phenomena. The channels need to be periodically dredged, with the consequent production of a filled ground big amount.

This sludge is produced by sedimentation phenomena and by channel bank washing away. They generally have the same chemical composition of the surrounding ground where they are scattered over.

Nevertheless, anthropic activities might alter the chemical composition of the ground, therefore its destination. If the regulation limit levels are exceeded, then the sludge has to be considered a waste and sent to a dumping (Bruno and Sgallari, 2004).

In the current work we consider a potentially polluted channel in the Padana plane which needs to be dredged, with the consequent production of about 240 m^3 of filled sludge.



(a) *(b)* *(c)*

Fig. 1. *Localization of the studied channel: (a) in the Italian peninsula and (b) in the Padania plane channel net, (c) a view of the channel*

The selection process for identifying the polluted channel strips is a typical problem of selection-precision-support. The actual regional and national norms don't consider this approach and, specifically, don't take into account the relation between estimation error / support dimension. This fact, among other problems, leaves undetermined the criteria for a sampling optimization. We will focus on these criteria for guiding the choice in some specific cases.

The surrounding industrial dumping leaded us to focus our analysis on heavy metal pollutants. The analysis started from the results of a subjective sampling plan, processed by the classical approach of Geostatistics: spatial variability definition, estimation on different supports and selection analysis (Bruno Sgallari and 2004).

The Geostatistical selection approach

The Geostatistical selection approach was defined in the past with reference to the mining world. Optimization criteria for sampling definition are deduced by using a cost-benefit analysis, taking into account sampling-exploitation-processing technical parameters and costs, as well as the economic value of the different ores.

The experimental data are used to estimate the true grade referred to the selection support.

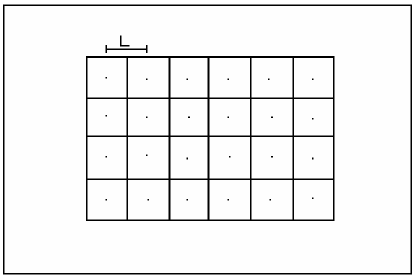


Fig. 2. *An example of sampling plan of lag L*

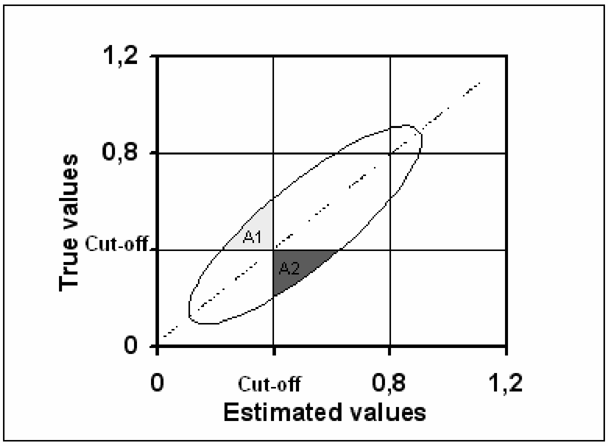


Fig. 3. *Scatter true – estimated values (ppm) (A_1 under-estimated values area, A_2 over-estimated values area)*

The cut-off value is the selection parameter to be applied on the estimated blocks grades; simply speaking the grade assuring receipts equal to the exploitation costs; reacher blocks potentially give a benefit, poorer ones give a lost. The estimation error depends on the chosen sampling density and on the selection support dimension; this allows the global evaluation of costs deriving from the misselection. In fact:

- the under-estimated unselected blocks identified in the area A_1 represent a lost of a potential benefit, given by the difference between receipts, function of grades R(t), and exploitation costs C:

$$C_{ue}=f(R(t_1),C, A_1) \quad (1)$$

– the over estimated selected blocks identified in the area A_2 represent a lost because the true grades don't allow recovering the exploitation costs:

$$C_{oe}=f(R(t_2),C, A_2) \quad (2)$$

These costs depends mainly on the area A_1, A_2 (number and grades of misselected blocks) which are directly linked to the estimation variance, which in turn is a function of the sampling lag (L).

$$C_{oue} = C_{oe} + C_{ue} = C_{oue}[\sigma^2_e(L)] \quad (3)$$

The sampling plan of given area, S_t, has a cost proportional to the number of samples, n_s, that is a cost inversely proportional to the sampling step:

$$C_s = c_s * n_s = c_s * (S_t / L^2) \quad (4)$$

The optimization of the total cost function gives the optimum sampling step.

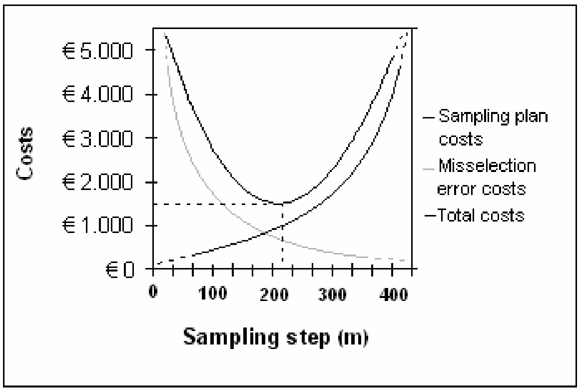


Fig. 4. *Sampling plan costs (light gray line), the estimation error costs (dark gray line) and the total costs (black line) versus the sampling step length. The minimization of total cost function gives the optimum sampling step*

The selection support does influence each of the above parameters, mainly exploitation costs, grades dispersion and misclassified areas; but generally it mainly depends on the design technical characteristics, often chosen before the selection process analysis is made.

The environmental application

In the case of an environmental project, as is the selection of sludge of a drainage channel, the optimization problem is complex. Indeed, the problem is conjugating the selection support dimension, the sampling density and the estimates precision, with a cost/benefit function which calls for an articulated economic analysis, depending on the situation at hand.

Normally the environmental cut-off values are the limit level specified by the regulation (Environmental Protection Italian Agency, 1999). Often they don't give any other indication than sending the selected volume to dumping, and leaving the unselected volume on site. Sometimes norms specify a sampling density, and seldom they define the tolerance on measured values. *Almost never norms make reference to an estimation process, to misclassification and to selection support.*

Cost analysis on a fixed support

Our analysis will start by considering a fixed selection support and we will focus on costs deriving by sampling density.

Given a sampling step and by a simple conditional simulation, it is possible an experimental calculation of under- and over estimated selection units. Repeating the experimental calculation for several simulations allows stable results. In this case we will proceed with single realizations that however allow getting meaningful information.

The over-estimation cost is given by sending to dumping blocks that could stay, therefore dredging, transporting and dumping costs, C_d. Again it is not difficult to define a cost function, independent on grades, but just dependent on the overestimated block numbers, that is on the overestimated areas A_2:

$$Co(Cd, A2) \qquad (5)$$

A simplified analysis refers the under-estimated cost to the damage incurred by the responsible in case the error is revealed. Such costs vary from the trial costs to several fine types. From a pragmatic point of view we can suppose that always the under-estimated cost can be reduced to a fine. Depending on the fine type, this can vary from being proportional to the environmental damage till being constant whatever the volumes and grades involved in the misclassification.

In general, from a modeling point of view we can propose a cost function which is dependent on volumes and true grades, $C_u(A_1,t_1)$. The true grades can be valued after a preliminary investigation.

Finally the former selection process can be proposed, by considering a total cost ,C_t, given by the sum of both misclassification costs; again these are a function of misclassification areas, directly linked to the estimation variances, that depend on sampling step:

$$Ct = Co(Cd ,A2) + Cu(t1,A1) = Ct [\quad 2e(L)] \qquad (6)$$

This is a reasoning valid for a fixed support and a given cut-off value.

Cost analysis varying the support

As commented above, the sampling support is not fixed so that two cases arise:

a. the whole field, St, has an estimated mean value lower than the actual cut off; from the economic point of view, it is convenient to choose as selection unit the whole area St, given the generally good precision of the "global estimation";
b. the whole field has an average concentration higher than the cut-off value; then it is convenient to introduce the selection support in the cost analysis for finding the couple of parameters, sampling step, L , and selection unit (su), that minimize the total costs:

The cut-off choice

Another aspect of the selection problem is the cut-off choice. Given a limit value, for example defined by law, its application as selection cut-off causes the two misclassification areas seen above. Again, the most difficult problem concerns the underestimated units not selected.

It can happen that be impossible to do any supplementary sampling and /or that the selection error costs caused by underestimation be too high or not acceptable in general. The reduction of such selection error, and consequently the reduction of its unsustainable costs, can be obtained by lowering the cut-off value with respect to the limit value. In such a way, the overestimation costs grow, because also many units with an estimated value less than the limit value are selected. But the underestimated erroneously leaved units can be reduced as much as necessary, and so the costs.

The following figure shows such option.

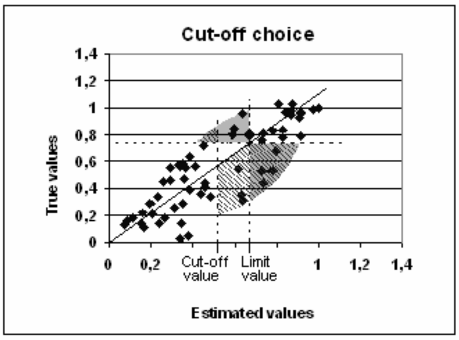


Fig. 5. *Reduction of the cut of value with respect to the limit value for reducing the selection error caused by underestimation*

Case study

The dredging of a potentially polluted drainage channel is regulated by local and national laws which fix the pollutant concentration limits and their application categories. Local laws describe the procedures for the specific cases.

As mentioned before, the studied channel is about 1 Km long and industrial dumping discharges in the first part of it. Consequently, a sampling plan was proposed (Bruno and Sgallari 2004) by using two different step lengths:

- 10 m on the area closer to the industrial dumping;
- 100 m with reference to the rest of the channel.

The layer subjected to dredging is 30 cm thick; samples of the underlying mud are also available for the analysis. The total amount of data is then 36 samples, half of them belonging to the superficial layer.

The cores were analyzed by focusing on heavy metals and these values were compared to the regulation limits. In the present paper, we will only consider lead, copper and zinc. Moreover, as the zinc data display values always above the law limits, we restricted the selection problem to the first two polluting metals. In fact, the selection is well defined: due to the very high zinc grade, the whole channel has to be dredged. Nevertheless, we will proceed *as if* Cu and Pb concentrations were the only decision criteria; this allows us to illustrate a general methodology.

In the following some general definitions are given and an experimental sensitivity analysis is presented for evaluating the effect of choosing a sampling density and a selection support. Finally we come back to the actual sampling and we identify the best selection support.

Cost analysis: definitions

Costs of samples, chemical analysis, mud treatment and disposal are generally known; this allows quantifying the sampling plan costs and the over-estimating costs. But, the evaluation of costs arising from an under-estimation of the actual values poses a practical problem.

First of all, the under-estimated costs can only refer to the damage incurred by the responsible if the error is revealed. In this specific case, laws provide a penal sentence and/or a fee and/or the obligation to restore the damage incurred. Only the last one is proportional to the wasted volume. The Italian law, in similar cases, provides a fine of 10000 €; the disposal costs are fixed by the National laws, as acknowledgement of the European one.

The cost of a conviction is given by the legal costs and by the monetization of the criminal record, which, in general, vary from person to person.

In this case both values can be considered constant and independent from the damage importance or from the judgment variability.

Given a channel 1 Km long and 1 m wide, the surface (S) considered is 1 Km^2; a standard sampling plan provides for one sample every L meters; the sample cost (cs) being about 100 €/sample, the sampling total cost (Cc) - function of the samples number (ns) - is given by:

$$Cc = cs * ns = 100\ €/sample * (1\ Km/L) \quad (7)$$

The over-estimated selection cost (*Co*) equals the disposal unit cost (*cd*) times the number of over-estimated units (*No*):

$$Co = cd * No \quad (8)$$

The under-estimation selection cost (*Cu*) equals the fine (*C*f = 10000 €) plus the legal matters monetization (*Ct*) and the waste disposal cost, proportional to number of under-estimated units (*Nu*):

$$Cu = Cf+Ct+cd * Nu \quad ()$$

The identification of the function correlating the misclassified blocks number with the precision and, consequently, with the sample density was empirically obtained by a classical geostatistical simulation.

Evaluation of under- and over-estimation costs

We simulated the three random functions Cu, Pb and Zn conditionally to the available data set and by using the nested nugget/gaussian model obtained experimentally (Bruno R. and Sgallari S., 2004). It is important to notice that the average copper grade is slightly above the cut-off referred by the Italian regulation tables. As usually, this simulation was regarded as 'true' regionalization, and we considered different sampling plans. Then, we estimated by co-kriging the distributions of copper and lead from each simulated sampling. Block grades were simply obtained as the arithmetic mean of internal simulated points; in our case a block is a volume where width and height are fixed (1 m and 30 cm respectively), and the length summarizes the support dimension.

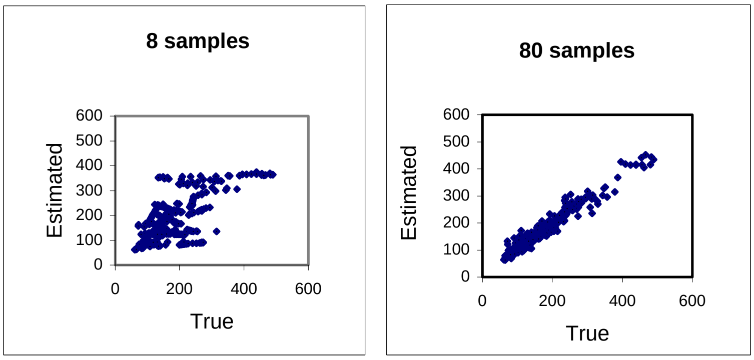


Fig. 6. *Scatter plot of true and estimated values of copper, by considering 8 and 80 samples with fixed selection support (length of 2 m). A poor amount of information leads to a highly dispersed estimation.*

Last step was the selection of estimated waste blocks and their comparison with the "true" values. This analysis, made for each sampling plan, returned the experimental function linking the misclassified units to the sampling density.

In case of more than one element, a block is selected for dumping if at least one of them trespasses its specific cut-off grade. This same criterion was applied for both, the estimated and "true" block grades; this procedure allows evaluating the amount of under-estimated (erroneously not selected) and over-estimated blocks (erroneously selected). The cut-off values defined by Italian norms (Italian Environment Ministry, 1999;.Italian Government, 1997) are:

Zn: 150 ppm Pb: 100 ppm Cu: 120 ppm.

As explained above, only lead and cupper grades were considered, thus zinc was simulated and estimated in order to improve the cokriging precision.

Figure 7 synthetically shows the experimental results, which help to identify an effective sampling plan and selection support size. The economic parameters considered are: 300 €/m^3 for exploitation, transportation and disposal of sludge; 15.000 € for fine and legal expenses; 100 €/sample for sampling and chemical analysis. These values refer to the Italian norms (Decr. Lgsl 22/97, art. 51/1) and to the specific case study.

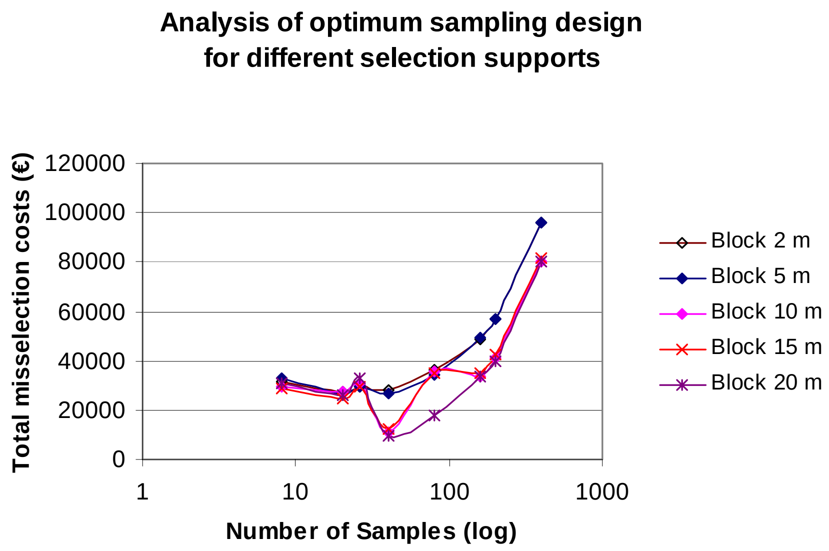


Fig. 7. *Experimental analysis of optimal selection costs for different sampling densities and selection supports.*

As the mean copper grade over the whole field trespasses the cut-off, we expected that the most convenient support dimension were the smallest. Indeed, the optimum choice is found nearby a sampling step of 20 meters, corresponding to a total of 40 samples, and a support dimension of 20 meters as well. The reason of such behavior is the particular spatial distribution of the highest grades. The requested precision needed in a small support scheme lets the sampling costs prevail over the gain given by a more effective selection.

The obtained results depend on the actual cut-off grade considered, in our case the Italian values of reference. Of course, different cut-off grades return different results.

This is an economic analysis that could be unsatisfactory from a purely environmental point of view. We must point out the lack of specific instructions regarding the support choice in matter of environmental remediation; this fact gives the responsibles the free hand of applying an economic criterion instead of a more conservative environmental one.

Actual cost analysis and selection support

The actual sampling is given and has not a regular step; in fact, the channel was divided in two segments, the first one (100 m long) with higher values of polluting content and a dense sampling rate (10 meters lag); the second one with just 8 samples, one every 100 m. In this case, the optimum pursuit refers only to the support size selection.

Again, blocks of different length were estimated by the actual sampling, which coincides with the simulated sampling, because the simulation is conditional. The block selection was repeated for estimated and "true" values, so that the under-estimation plus over-estimation costs were obtained. By considering also the costs for dumping the correctly selected blocks, it is possible to obtain the total cost of for any given selection support. The results are shown in Fig. 8.

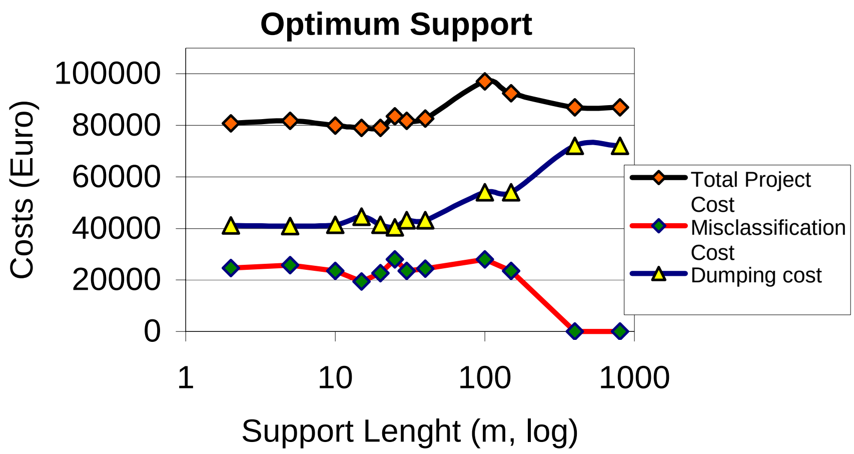


Fig. 8. *Identification of optimum selection support: actual functions of misselection, dumping and total costs versus selection support dimension (block length) for fixed Pb/Cu cut-offs.*

The graph confirms that an increase of selection support reduces the misclassification costs, given the higher estimates precision. And, as expected, the dumping costs increase because more material than necessary is sent to dumping. This trend is strictly linked to a mean grade of pollutants higher than their cut-off grades. Finally, the total costs of dredging do depend on the selection support chosen, at least if a 40 m blocks length is exceeded. This is due, essentially, to the geometry of the actual sampling (irregular) and to the actual distribution of the grades. In effect, the denser sampling refers to the more polluted area and this allows a better estimation of the "sensible" blocks/area.

In practice, we can consider as an effective selection support blocks of about 15 m length, a solution that fixes the total minimum cost of 80.000 €.

Conclusion

A cost-based approach for the optimum sampling design in an environmental project has been successfully tested. We obtained a definition of variable and fixed costs linked to the over- and under-estimation of pollutant grades over a decisional domain (support). We proceeded to a simulation of the over- and underestimated blocks with respect to the two governing parameters, sampling density and support selection, with the aim to give a general strategy for the optimal choices.

Finally, for the actual sampling, we found the optimum support choice again by evaluating the misselected units.

It must be stressed that such results strictly depend on the considered cut-off values. Generally, if the mean grade on the field is below the law limits, the choice of the total area as selection unit is more convenient from an economic point of view, but not from an environmental point of view. Again, the lack of any indication with reference to a selection volume means that a "steered" analysis, formally correct, can favour an economic interest as regards as the environmental one.

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